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PLANE STRAIN FRACTURE-TOUGHNESS DATA FOR SELECTED METALS AND ALLOYS

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DMIC Report S-28
June, 1969

PLANE-STRAIN FRACTURE-TOUGHNESS DATA FOR SELECTED METALS AND ALLOYS

by

J. E. Campbell

to

OFFICE OF THE DIRECTOR OF DEFENSE
RESEARCH AND ENGINEERING

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PLANE-STRAIN FRACTURE-TOUGHNESS DATA FOR SELECTED METALS AND ALLOYS

J. E. Campbell*

SUMMARY

Plane-strain fracture-toughness (K_{Ic}) parameters may be used to estimate critical flaw sizes in structural metals subjected to known stresses at specified temperatures. Previous toughness parameters for evaluating high-strength alloys provided only empirical data that could not be used directly in design. This report contains the first compilation of available K_{Ic} data and is the result of considerable interest during the past few years in developing test methods for obtaining these data.

Test specimens that have been used in obtaining K_{Ic} data include notched-and-precracked bend specimens, compact K_{Ic} tension specimens, single-edge-notch tension specimens, and part-through-cracked tension specimens. Standard procedures developed for bend-test specimens and compact K_{Ic} tension specimens apply only to products of relatively thick section such as plate and forgings.

The report is divided into sections on:

Aluminum alloys
High-strength alloy steels
Intermediate- and low-strength steels
Precipitation-hardening stainless steels
Titanium alloys
Nickel-base Alloy 718
Beryllium.

Data on the aluminum alloys are limited to the 2000- and 7000-series alloys. The high-strength alloy steels include the maraging steels, 9Ni-4Co steels, and lower alloy steels such as AISI 4340, D6ac, 300M, and H-11. The intermediate-strength steels include those that have been considered for submarine hulls, atomic-reactor vessels, and steam-turbine rotors. Data for the stainless steels are limited to the precipitation-hardening grades. Available room-temperature data for the titanium alloys are for solution-treated-and-aged alloys such as Ti-6Al-4V and Ti-6Al-6V-2Sn. Limited data are available for several titanium alloys at cryogenic temperatures. The only nickel-base alloy for which valid K_{Ic} data are available is Alloy 718. Limited K_{Ic} data also are available for beryllium sheet and hot-pressed products.

* Associate Fellow, Battelle Memorial Institute, Columbus, Ohio.

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INTRODUCTION

DMIC Report 207* of August 31, 1964, described the test methods that had been proposed up to that time for making plane-strain fracture-toughness tests on high-strength alloys. The report also pointed out the significance of information that may be obtained from such tests, including calculation of critical flaw sizes from fracture-toughness data. The fact that plane-strain fracture-toughness data can be used to estimate critical flaw sizes when designing and selecting materials for highly stressed structures represents a significant advantage over various empirical methods for rating toughness of high-strength alloys. In 1964, however, there were no recognized standard methods for making plane-strain fracture-toughness tests, and experimental data were available for only a few alloys. In addition, procedures for establishing validity of the test data had not yet been developed.

In the past 5 years, two proposed test methods for measuring plane-strain fracture-toughness parameters for high-strength alloys have been developed by ASTM Committee E24. These methods are described in the "green pages" of ASTM Standards, Part 31, May, 1969, under the title "Proposed Method of Test for Plane-Strain Fracture Toughness of Metallic Materials".(1) The methods described are for a notched-and-fatigue-cracked bend specimen and a notched-and fatigue-cracked compact K_{Ic} tension specimen. Other plane-strain-fracture test methods, such as methods for testing circumferentially notched round bars and part-through-cracked flat specimens, have not been considered suitable for standardization by ASTM Committee E24.

All of the test methods for measuring plane-strain fracture-toughness parameters are much more complex than other methods for determining short-time mechanical properties of high-strength alloys. Preparing the test specimens and conducting the tests also are more costly than for other short-time tests. In addition, it should be pointed out that the specimen size requirements for plane-strain fracture-toughness tests depend on the toughness. The procedures that describe the method of test also describe a method for estimating the minimum specimen size requirement based on the yield strength and elastic modulus. However, a better estimate of minimum specimen size may be made if, as discussed later, one knows the approximate plane-strain fracture-toughness value for the alloy under consideration. (See Table 1.)

TABLE 1. DIMENSIONS AND ESTIMATED MEASUREMENT CAPACITIES OF VARIOUS SIZES OF COMPACT K_{Ic} TENSION SPECIMENS(5)

Type	Estimated Measurement Capacity(a)		Tentative Overall Dimensions		
	K_{Ic}/σ_{ys}	$(K_{Ic}/\sigma_{ys})^2$	Thickness, in.	Height, in.	Width, in.
1T-CT	0.63	0.40	1	2.4	2.5
2T-CT	0.90	0.80	2	4.8	5.0
3T-CT	1.10	1.20	3	7.2	7.5
4T-CT	1.30	1.60	4	[illegible]	10.0
6T-CT	1.60	2.40	6	14.4	15.0
8T-CT	1.80	3.20	8	19.2	20.0
10T-CT	2.00	4.00	10	24.0	25.0
12T-CT	2.20	4.80	12	28.8	30.0

(a) Based on currently suggested ASTM E-24 minimum size criterion, a, and $B \geq 2.5\ (K_{Ic}/\sigma_{ys})^2$, where a is crack length in inches.

* Copies of DMIC Report 207 are available from Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia 22151. Hard copies are $3.00; microfiche, $0.65 each. Request AD 608[illegible]01.

Some hardware contracts from certain Government agencies require information on fracture toughness of the high-strength alloys that are to be used in structures. Aerospace contractors, research laboratories, and the arsenals are using fracture-toughness tests to show what materials and material treatments provide the best toughness for certain critical applications. Alloy producers are finding that they need information on fracture toughness of their alloys in order to respond to customer inquiries. Furthermore, fracture-toughness testing is being used to analyze structural failures. Because of these factors, there is considerable interest in available plane-strain fracture-toughness data by metallurgists and materials engineers who may be concerned with comparing test data, making fracture-toughness tests, or selecting materials to meet certain toughness requirements. Furthermore, structures engineers and designers also have requested plane-strain fracture-toughness data for use in design.

This is the first DMIC compilation of available plane-strain fracture-toughness data for high-strength alloys. In time, additional data will become available and will be reported in other DMIC documents.

FRACTURE-TOUGHNESS TESTING

By custom, critical plane-strain stress-intensity factors have been designated as K_{Ic} values. These values have units of stress x $\sqrt{\text{length}}$. The unusual units are the result of the factors that appear in the stress-intensity equations based on linear, elastic fracture mechanics.(2) The K_{Ic} value itself is a factor that may be used in calculating the critical crack size in a high-strength-alloy component when it is subjected to a known stress level. In these calculations, the K_{Ic} values are squared, thereby eliminating the square-root unit.

The critical-stress-intensity factor, K_{Ic}, is the critical value of the stress-intensity factor, K_I, at which crack propagation first occurs under conditions of high constraint to plastic deformation in a neutral environment during application of load at a relatively slow rate. High constraint to plastic deformation implies that the conditions are essentially plane strain in the path of the crack. The neutral environment refers to room-temperature air with normal humidity. Unusual variations in humidity are likely to affect the results of plane-strain fracture-toughness tests for certain materials. High humidity may cause initiation of cracking at a lower load than normal because of the stress corrosion effect.

Testing procedures in stress-corrosion or fatigue studies also may involve the use of notched-and-fatigue-cracked specimens and the elastic-fracture mechanics approach. In stress-corrosion testing, for example, a notched-and-precracked specimen may be loaded to a certain stress-intensity level (K_I) and subjected to a specified corrosive environment. The highest stress-intensity level at which such specimens do not fail in an extended time period is the threshold stress-intensity level for stress-corrosion cracking (K_{Iscc}) for the alloy in the environment.

Crack propagation during fatigue cycling of notched specimens also may be based on the fracture-mechanics approach. The minimum and maximum cyclic

loads are controlled to yield a specific initial stress-intensity range, ΔK_I, for the alloy being evaluated.

Information on crack-growth rates and threshold values of stress intensity are important for consideration when selecting materials for many highly stressed components. Furthermore, techniques are being developed to estimate the service lives of components in which it is assumed that the initial crack size is just a little smaller than the critical crack size as determined on the initial proof-test loading. Because of these and other developments, it appears that the application of plane-strain fracture-toughness parameters for evaluating high-strength alloys will increase. However, the purpose of this report is to provide a collection of available plane-strain fracture-toughness (K_{Ic}) data representing the current state of the art. Further developments could be subjects for future DMIC reports or memoranda.

Data reported in the following tables and figures do not necessarily comply with the requirements of the ASTM Proposed Method of Test, since data are reported for bend specimens that were subjected to four-point bending (rather than three-point bending), for single-edge-notch tension specimens, and for part-through-crack tension specimens. Supplementary information was used to check the validity of the reported values where possible. Some data are reported in spite of certain deficiencies because they were the only data for a certain material or the data showed certain trends, such as effect of testing temperature or effect of loading rate. The part-through-crack specimens show the effect of crack propagation in a different direction than the usual edge-notch specimens.

In comparing data, effect of crack orientation and direction of crack propagation must be considered along with such factors as heat treatment, yield strength, microstructure, rate of loading, testing-machine stiffness, and testing temperature. Notations for crack-propagation orientations are shown in Figure 1. The usual edge-notch longitudinal specimen is the RW orientation, and the usual edge-notch transverse specimen is the WR orientation. The TW and TR orientations represent short-transverse testing directions. Heat-treatment and yield-strength data are given for each series of specimens in Tables 2-21. The recommended range for the loading rate is given in the Proposed Method of Test.(1) The usual loading time to fracture is from 1 to 3 minutes. However, K_{Ic} data obtained at higher loading rates are presented in the latter part of this report. Effects of low and elevated temperatures on K_{Ic} values also are illustrated there.

It is intended that the data represent that typical of a specific alloy in the stated condition. However, with only limited data and supplemental information, typical data are often difficult to identify. Much of the available data were not included in Tables 2-21 because the data did not appear to be typical or was not valid according to validity tests described in the Proposed Method of Test. Some invalid data are intentionally included in the tables to show what might be expected, and some invalid data also may be inadvertently included because of the intent to provide as much data as possible, even though all of the supplementary data may not be available.

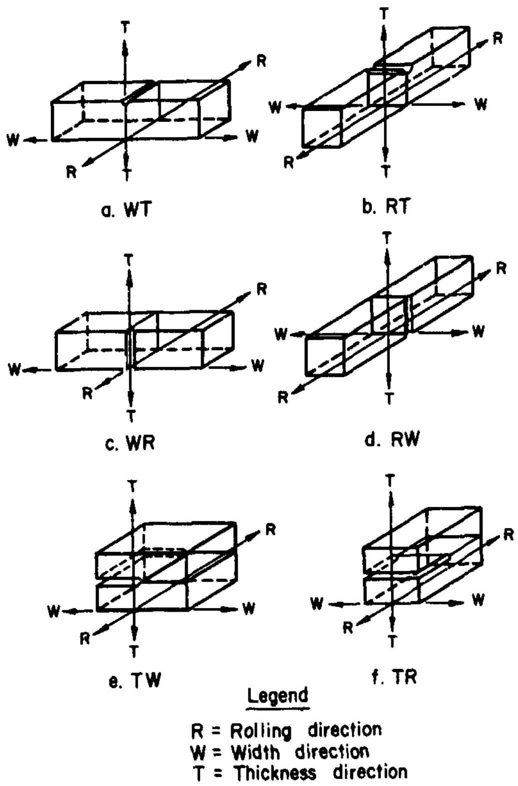


FIGURE 1. CRACK-PROPAGATION DIRECTIONS

A number of precautions are emphasized in the Proposed Method of Test which must be followed in order to ensure valid data. Among these are the selection of a specimen size that is adequate to approach plane-strain fracturing conditions, the use of low loads in developing the fatigue cracks, the use of friction-free fixtures, and a check of the secant intercept point to ensure initiation of fracture at that load. In addition, one should calculate values for 2.5 (K_Q/yield strength)^2.* These values should be equal to or less than the thicknesses of the specimens. This is an arbitrary requirement for validity of the data, but it is a specific requirement of the test method and indicates that the plastic zone at the leading edge of the crack was of limited size when fracturing was initiated.

However, the requirement that the thickness be equal to or greater than 2.5 (K_Q/yield strength)^2 applies only when K_Q is equal to or larger than the true value of K_{Ic}. If K_Q is smaller, the required thickness will be underestimated. This situation has occurred in several laboratories when making tests on titanium alloys. The K_Q values were assumed to be valid, since they apparently met the requirements of the test. However, the fractures in these specimens showed considerable shear-lip area (about 75 percent in one instance). The large shear-lip areas indicate that plane-strain conditions had not been achieved. Tests on larger specimens resulted in higher K_Q values that complied with the requirements of the test and also resulted in smaller shear-lip areas in the fractures. The valid tests also met the requirements for specimen thickness based on the yield strength/modulus ratio in Reference (1). Any questionable results of fracture-toughness tests, especially on alloys for which there has been no prior data, should be examined carefully before they are reported as valid K_{Ic} data.

*K_Q is the provisional value of K_{Ic}.

Test Specimen Designs

Plane-strain fracture-toughness data can be obtained only by simulating plane-strain fracturing conditions in test specimens. In order to achieve plane-strain conditions from a practical standpoint precracked specimens are loaded in tension or in bending until fracturing occurs at the leading edge of the crack. The specimens must be large enough so that when fracturing starts there is only a negligible plastic zone ahead of the crack front. Under these conditions, linear elastic fracture mechanics can be applied in making the stress analysis. When cracking occurs under these conditions, the gross stress for fracture initiation is lower then the yield stress. Furthermore, the fracture appearance is practically the same as for fractures in structures that have failed catastrophically at gross stresses lower than the yield stress. Structural failures of this type nearly always start at flaws.

In order to achieve these conditions, the size of the specimen must be large enough to provide sufficient constraint at the leading edge of the crack to minimize plastic-zone formation. The minimum specimen thickness is indicated by the same equation as discussed previously:

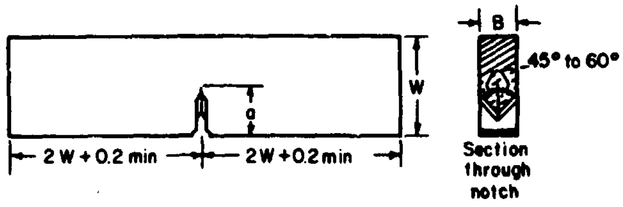
$$B = 2.5\left(\frac{K_Q}{Y.S.}\right)^2$$

where B is thickness in inches and Y.S. is the yield strength in pounds per square inch. To comply with this requirement, specimens of an aluminum alloy, for example, with a yield strength of 70,000 psi and K_{Ic} (about 35 ksi $\sqrt{in.}$ based on past data, should be at least 0.625 inch thick to provide valid K_{Ic} values. If this same alloy is procured as 1/2-inch plate, specimens of the required thickness cannot be obtained from it, and the plate cannot be evaluated. Lower strength aluminum alloys would require specimens thicker than 0.625 inch. When evaluating the fracture toughness of intermediate-strength steels, specimens as thick as 12 inches have been used in order to obtain essentially plane-strain conditions and valid data. Consequently, the required size of specimen will be governed by the strength and toughness of the alloy to be evaluated.

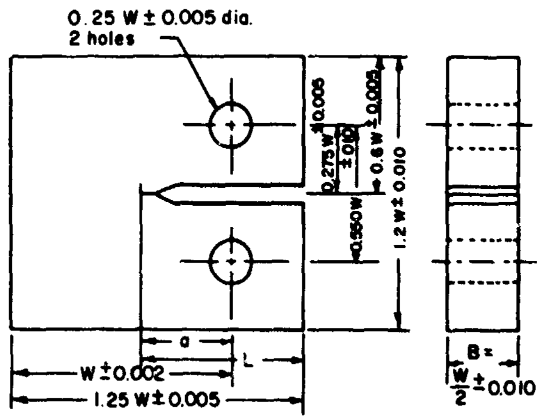
Even though the ASTM's "Proposed Method of Test for Plane-Strain Fracture Toughness of Metallic Materials"(1) recognizes only the precracked-three-point bend test and the compact K_{Ic} tension test for obtaining K_{Ic} data, other types of specimens have been used for obtaining plane-strain fracture-toughness data. Since significant data have been obtained using these other types of specimens as well as the proposed types, data presented in the tables and figures of this report are for specimens of a variety of types, including:

- Notched-and-precracked bend specimens with three-point loading
- Notched-and-precracked bend specimens with four-point loading
- Compact K_{Ic} tension specimens
- Single-edge-notch tension specimens
- Part-through-crack tension specimens.

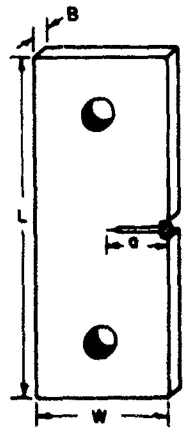
Typical specimen designs are shown in Figure 2.



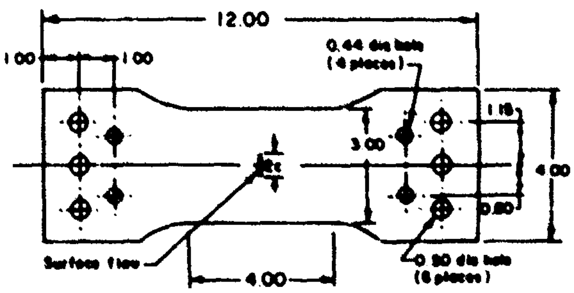
a. Precracked - Bend Specimen Design with Chevron Notch



b. Compact K_{Ic} Tension Specimen Design



c. Typical Single - Edge - Notch Specimen Design



d. Typical Part - Through - Crack Specimen Design

FIGURE 2. TYPICAL TEST-SPECIMEN DESIGNS

Drawings of the three-point-bend specimen and the compact K_{Ic} tension specimen and testing fixtures are included in the ASTM Proposed Method.(1) Dimensions and estimated measurement capacities for various sizes of compact K_{Ic} tension specimens are shown in Table 1. Designs and testing procedures for part-through-crack specimens are discussed by Randall(3) and Tiffany and Masters(4). A number of variations of these specimen designs have been used, and specimen dimensions are included in the tables of data when available.

The ASTM Proposed Method specifies that the notch-plus-crack length be equal to 0.45 to 0.55 of the specimen width for the bend specimens. In some instances, apparently valid data have been obtained with shorter crack lengths, and such data are included in some of the tables. Information on crack lengths is also included in the tables when available.

Furthermore, for some of the bend-test data, the width-to-thickness ratios of the bend specimens were not necessarily the same as recommended in the Proposed Method (in which width/thickness equals 2). Data for width and thickness of the specimens are included in the tables when available.

For future fracture-toughness testing programs, it is recommended that recognized test-specimen designs and procedures be used, if possible, so there will be no uncertainty regarding the validity of the results.

Alloys for Evaluation by K_{Ic} Tests

In general, plane-strain fracture-toughness testing has been limited to high-strength aluminum alloys, heat-treated alloy steels including maraging steels and heat-treatable stainless steels, and high-strength titanium alloys. As pointed out previously, intermediate-strength steels also can be evaluated by K_{Ic} tests if very thick specimens are used. Intermediate-strength aluminum and titanium alloys also could be evaluated by K_{Ic} tests if the specimens were large enough to approach plane-strain conditions at the initiation of fracturing. In addition, K_{Ic} data are available for one nickel-base alloy (Alloy 718). Several attempts also have been made to determine K_{Ic} values for beryllium.

If a certain component is to be exposed to below-ambient temperatures, fracture-toughness data for potential alloys for the component obtained at the lowest service temperature should be used in selecting the alloy for this component. If the lowest service temperature is considerably below ambient, the alloy selected for the component based on the low-temperature K_{Ic} data might not be the same alloy that one would select based on ambient-temperature data. Fracture-toughness values for high-strength alloys, particularly the low-alloy steels, decrease as the temperature is decreased. This trend will be discussed later.

PLANE-STRAIN FRACTURE-TOUGHNESS DATA

Aluminum Alloys

Fracture-toughness data obtained on precracked-bend-test specimens of four aluminum alloys of the 2000 series and five alloys of the 7000 series are shown in Table 2. Most of the specimens had chevron-type notches as illustrated in Figure 2(a), and the remainder had straight-across notches. According to available information on these tests, all of the K_{Ic} data are valid except for the longitudinal specimens of X7007 alloy. K_{Ic} data for both the 2000- and 7000-series alloys fall within the same range (19 to 35 ksi $\sqrt{\text{in.}}$). Fracture toughness of the longitudinal specimens (RW orientation) appears, in most cases, to be slightly greater than that of the corresponding transverse specimens (WR orientation).

Data in Table 3 also are for the 2000- and 7000-series aluminum alloys, but they represent results from tests on single-edge-notch tension, compact K_{Ic} tension, and precracked bend specimens for three- and four-point loading. The K_{Ic} values in parentheses in Table 3 are invalid according to the $B \geq 2.5\,(K_{Ic}/Y.S.)^2$ criterion.

Table 4 shows data from single-edge-notch tensile specimens from aluminum-alloy extrusions. Specimens of different sizes were obtained from extrusions having various thicknesses. In some instances, valid data from specimens of different sizes were averaged to obtain the results shown in the table. Some of the specimens in the "Heat Treated by User" temper (T62) were not large enough to yield valid data.

Effect of temperature over the range -75 to 150 F on the fracture toughness of 7079-T6 aluminum alloy is shown in Table 5. Varying the testing temperature over this range appears to have only a very slight effect on the fracture toughness of this alloy.

Tables 2, 3, 4, and 5 all contain data for 7079-T6 alloy on transverse (WR) specimens of various types. A comparison of the data for specimens of this alloy is as follows:

Alloy	Table No.	Yield Strength, ksi	Specimen Type(a)	Average K_{Ic}, ksi $\sqrt{\text{in.}}$
7079-T6	2	74.2	NB-3	25.3(b)
(WR)	2	72.8	NB-3	24.0(b)
	3	74.9	SEN	21.7
	4	71.2	SEN	29.2(b)
	5	63.5	CT	28.2(c)

(a) NB-3 = notched bend specimens with three-point loading; SEN = single-edge-notch specimens; CT = compact tension specimens.
(b) T651 temper.
(c) From 3-inch-thick forged plate.

The average fracture-toughness values are seen to vary from about 22 to about 29 ksi $\sqrt{\text{in.}}$ The observed scatter in average K_{Ic} values is believed to arise from several sources, including variations in yield strength, section size, processing variables, other heat-to-heat variations, and stress analysis used for the different types of specimens.

TABLE 2. AVERAGE PLANE-STRAIN FRACTURE-TOUGHNESS DATA FOR ALUMINUM-ALLOY PLATE TESTED AS PRECRACKED BEND SPECIMENS AT ROOM TEMPERATURE

Alloy	Temper	Plate Thickness, in.	Test Specimen (a) Orientation	Yield Strength, ksi	Average K_{Ic}, ksi $\sqrt{in.}$	$\left(\frac{K_{Ic}}{Y.S.}\right)^2$	Bend Test Span,(b) in.	Specimen Dimensions, in. Thickness	Width	Crack Length(c)	No. of Tests	Reference
2020	T651	1.37	L	77.0(c)	22.3	0.084	12.0	1.37	3.0	1.5	3	(6)
			T	77.0(c)	19.2	0.062	12.0	1.37	3.0	1.5	3	(6)
X2021	T81	1/2, 1.0	L	65.3	29.6	0.20	4,8	1/2, 1	1,2	0.45, 0.90	- -	(7)
		1/2, 1.0	T	64.1	23.0	0.13	4,8	1/2, 1	1,2	0.45, 0.90	- -	(7)
2024	T851	1.38	L	65.6	22.9	0.12	12.0	1.38	3.0	1.5	4	(6, 11)
			T	64.4	18.8	0.085	12.0	1.38	3.0	1.5	4	(6, 11)
2024	T851	1-3/8	T	64.4	22.0	0.12	- -	0.5-1.3	28	- -	10	(8)
2024	T851	1.00	- -	64.6	22.2	0.13	8.0	1.00	2.0	0.28	2(e)	(9)
2024	T851	1.00	- -	65.0	22	0.12	6.6	0.8	1.6	0.8	4	(10)
2219	T851	1.4	L	51.0	35.5	0.48	12.0	1.4	3.0	1.5	2	(11)
			T	50.8	33.3	0.43	12.0	1.4	3.0	1.6	4	
7001	T75	1.37	L	71.0(c)	24	0.11	12.0	1.37	3.0	1.5	3	(6)
			T	70.0(c)	22	0.099	12.0	1.37	3.0	1.5	3	(6)
X 7007	T6E136	1/2, 1.0	L	68.6	(45.0)(d)	0.43	4,8	1,2	1/2,1	0.45, 0.90	- -(e)	(7)
		1/2, 1.0	T	67.0	37.5	0.31	4,8	1,2	1/2,1	0.45, 0.90	- -(e)	(7)
7075	T651	1.38	L	75.4	28.1	0.14	12.0	1.38	3.0	1.5	1	(6, 11)
			T	77.7	22.7	0.085	12.0	1.38	3.0	1.5	2	(6, 11)
7075	T6511	1.2	L	79.2	25.6	0.10	12.0	1.2	3.0	1.5	2	(11)
			T	75.4	24.6	0.11	12.0	1.2	3.0	1.5	2	
7075	T7351	- -	L	58.3	32.9	0.32	12.0	1.38	3.0	1.5	2	(11)
			T	56.8	28.1	0.24	12.0	1.38	3.0	1.5	2	
7075	T7351	1-3/8	T	56.8	28.0	0.24	- -	1-1.3	28	- -	6(e)	(8)
7075	T73511	1.2	L	63.6	35.0	0.30	12.0	1.2	3.0	1.5	2	(11)
			T	62.2	30.7	0.24	12.0	1.2	3.0	1.5	2	
7079	T651	1.38	L	77.6	31.0	0.16	12.0	1.38	3.0	1.5	2	(6, 11)
			T	74.2	25.3	0.12	12.0	1.38	3.0	1.5	2	(6, 11)
7079	T651		T	72.8	24.0	0.11	- -	0.5-1.3	28	- -	10	(8)
7178	T651		L	81.0	26.2	0.10	8.0	1.0	2.0	1.0	4	(11)
			T	80.8	23.4	0.084	8.0	1.0	2.0	1.0	4	(11)
7178	T6511	1.2	L	86.4	18.7	0.047	12.0	1.2	3.0	1.5	2	(11)
			T	82.0	19.5	0.057	12.0	1.1	3.0	1.5	2	(11)

(a) L = longitudinal or RW orientation, T = transverse or WR orientation.
(b) For three-point loading.
(c) Approximate values.
(d) K_{Ic} value does not comply with requirement that specimen thickness be equal to or greater than $2.5\,(K_{Ic}/Y.S.)^2$.
(e) Specimens had straight-across notches. Other specimens had chevron notches.

TABLE 3. AVERAGE PLANE-STRAIN FRACTURE-TOUGHNESS DATA FOR ALUMINUM ALLOYS AT ROOM TEMPERATURE

Alloys	Temper	Yield Strength, ksi	Tensile Strength, ksi	Specimen Type(a)	Test Specimen Orientation(b)	Average K_{Ic},(c) ksi $\sqrt{in.}$	$\left(\frac{K_{Ic}}{Y.S.}\right)^2$	No. of Tests	Specimen Dimensions, in. Thickness	Width	Crack Length	Reference
2020	T651	76.3	80.4	SEN	WR	16.4	0.046	1	1.0	5.0	1.6	(12)
2024	T4	48.1	72.4	SEN	RW	(45.8)	0.87	3	1.0	5.0	1.6	(12)
2024	T351	43.9	65.8	SEN	WR	(30.5)	0.48	4	1.0	5.0	1.6	(12)
2219	T87	57.9	72.0	SEN	RW	33.0	0.33	2	1.0	5.0	1.6	(12)
		55.2	72.0	SEN	WR	29.9	0.29	2	1.0	5.0	1.6	(12)
2219	T851	59.3	73.4	SEN	RW	36.0	0.37	4	1.0	5.0	1.6	(12)
				NB-3	RW	(38.3)	0.42	3	1.0	2.0	1.0	(12)
		58.4	74.3	SEN	WR	(37.3)	0.41	8	1.0	5.0	1.6	(12)
				NB-4	WR	35.5	0.37	4	1.0	2.0	1.0	(12)
2219	T851	49.3	65.8	CT	WR	28.7	0.34	16	1-1-3/8	2B	1-1.6	(8)
7075	T6	78.5	90.0	SEN	RW	32.9	0.18	6	1.0	5.0	1.6	(12)
		77.8	88.2	SEN	WR	23.9	0.095	1	1.0	5.0	1.6	(12)
7075	T6	77.0	- -	SEN	RW	(25.5)	0.10	5	0.24	2.25	0.75	(13)
		71.5	- -	SEN	RW	26.7	0.14	5	0.375	2.25	0.60	(13)
		76.4	- -	SEN	RW	27.3	0.13	5	0.51	2.25	0.80	(13)
7075	T7351	66.7	76.6	SEN	RW	32.5	0.24	4	1.0	5.0	1.6	(12)
		64.9	75.5	SEN	WR	26.7	0.17	4	1.0	5.0	1.6	(12)
		64.9	75.5	NB-4	WR	26.1	0.16	4	1.0	2.0	1.0	(12)
7079	T6	74.9	85.4	SEN	WR	21.7	0.084	1	1.0	5.0	1.6	(12)
7106	T63	52.5	60.8	SEN	WR	(40.8)	0.60	3	1.0	5.0	1.6	(12)
7039	T6	57	- -	CT	- -	19	0.11	1	4	12	- -	(14)
Forging, 4 x 10 x 12 in.		59(d)	- -	CT	- -	17(d)	0.083	1	4	12	- -	(14)

(a) SEN = single-edge-notch specimen, NB-3 = notch-bend specimen with three-point loading, NB-4 = notch-bend specimen with four-point loading, CT = compact K_{Ic} tension specimens.
(b) See Figure 1 for orientation code.
(c) K_{Ic} values (in parentheses) do not comply with requirement that specimen thickness be equal to or greater than $2.5(K_{Ic}/Y.S.)^2$.
(d) Tested at 0° F.

TABLE 4. AVERAGE PLANE-STRAIN FRACTURE-TOUGHNESS DATA FOR ALUMINUM-ALLOY EXTRUSIONS TESTED AS PRECRACKED SINGLE-EDGE-NOTCH TENSILE SPECIMENS AT ROOM TEMPERATURE(15)

Alloy	Temper	Extrusion Thickness, in.	Test Specimen Orientation	Yield Strength,(a) ksi	Average K_{Ic},(b) ksi $\sqrt{in.}$	$\left(\frac{K_{Ic}}{Y.S.}\right)^2$	Specimen Dimensions, in. Length	Width	Thickness	Crack Length	No. of Tests
2024	T8510	0.5-4.0	L	66.0	27.9(c)	0.18	4W	2.2-6.0	0.5-1.8	0.78-20	10
			T	65.0	17.5(c)	0.073	4W	0.9-1.5	0.2-0.5	0.3 -0.5	6
7075	T6510	0.21-5.0	L	78.0	28.7(c)	0.13	4W	1.5-6.0	0.21-2.0	0.5-2.0	12
			T	68.0	23.7(c)	0.12	4W	0.9-1.5	0.2-0.5	0.3-0.6	11
7075	T73510	0.9-2.8	L	67.0	33.8(c)	0.25	4W	1.5-6.0	0.75-1.0	0.7-1.7	5
		5.0	T	53.6	21.7(c)	0.16	6	1.5	0.5	0.5	2
7079	T6510	0.5	L	73.8	30.9	0.15	6	1.5	0.49	0.5	2
			T	71.2	29.2	0.16	6	1.5	0.49	0.6	2
7178	T6150	0.18-2.2	L	86.0	21.4(c)	0.062	4W	0.9-3.0	0.18-1.0	0.4-1.0	9
			T	79.0	20.6(c)	0.068	4W	0.9-1.5	0.18-0.5	0.4-0.5	8
			Extrusions in the "Heat Treated by User" Tempers								
2014	T62	0.3	L	65.0	(28.6)	0.19	3.75	0.93	0.296	0.3	2
			T	62.0	(28.0)	0.20	3.75	0.93	0.268	0.3	2
7075	T62	1.2	T	70.0	23.8	0.11	6	1.5	0.50	0.52	2
7079	T62	0.22	L	75.6	(35.8)	0.22	3.75	0.88	0.223	0.28	2
7178	T62	0.4, 1.5	L	88.0	23.3	0.070	6	1.5	0.404	0.5-0.6	2
			T	83.0	22.6	0.074	3.75,6	0.94,1.5	0.3,0.5	0.5	4

(a) Approximate values (values depend on composition and thickness)
(b) K_{Ic} values in parentheses do not comply with requirement that specimen thickness be equal to or greater than 2.5 $(K_{Ic}/Y.S.)^2$.
(c) Averages recalculated from original data.

TABLE 5. AVERAGE PLANE-STRAIN FRACTURE-TOUGHNESS DATA FOR 7079-T6 ALUMINUM-ALLOY PLATE TESTED AS COMPACT K_{Ic} TENSION SPECIMENS IN THE RANGE FROM -75 TO 150 F(16)

Alloy	Form	Aging Treatment	Testing Temp., F	Yield Strength, ksi	Test Specimen Orientation	Average K_{Ic}, ksi $\sqrt{in.}$	$\left(\frac{K_{Ic}}{Y.S.}\right)^2$	Specimen Thickness, in.	No. of Tests
7079-T6	3-In.-thick forged plate	RT 5 days, 240 F 48 hr	75	63.5	RW	32.1	0.26	2.00	7
			75	63.5	WR	28.2	0.20	2.00	2
			150	63.0	RW	35.5	0.32	2.00	2
			100	62.0	RW	34.7	0.31	2.00	2
			32	65.6	RW	33.8	0.26	2.00	2
			0	69.2	RW	32.7	0.21	2.00	2
			-40	68.4	RW	32.6	0.23	2.00	2
			-75	68.6	RW	34.0	0.24	2.00	2

The variation in K_{Ic} values over a range of yield strengths for aluminum alloys was studied at the Naval Research Laboratory (NRL); their data are shown in Figures 3 and 4. The K_{Ic}-OMTL line in Figure 3 is the optimum-material trend line, which indicates that, for the optimum materials, the K_{Ic} values decrease as the yield strength is increased. There also appears to be a correlation between K_{Ic} values and dynamic tear-test energy as shown for NRL data in Figure 4.

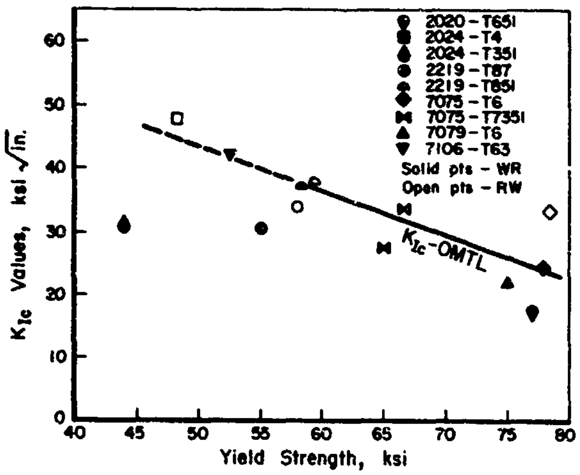


FIGURE 3. VARIATION IN K_{Ic} VALUES WITH YIELD STRENGTH FOR ALUMINUM ALLOYS OF 1-INCH PLATE[12]

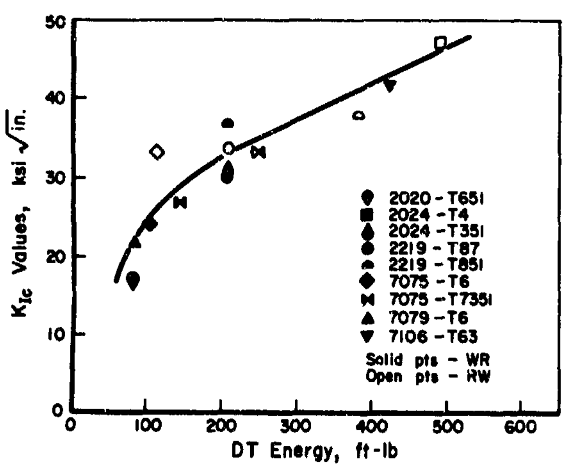


FIGURE 4. CORRELATION OF K_{Ic} VALUES WITH DYNAMIC TEAR-TEST ENERGY[12]

Tests at Boeing on part-through-crack specimens of 2219-T6E46 aluminum-alloy plate of specimens representing parent metal and weld metal resulted in K_{Ic} values of 35.7 ksi $\sqrt{in.}$ for the parent metal and 32.0 ksi $\sqrt{in.}$ for the weld metal.[17] The yield strength of the plate was 39,400 psi and the tensile strength was 58,000 psi.

Fracture toughness tests on part-through-crack specimens in which the crack was in weld metal in 2219-T851 aluminum alloy have been conducted at various temperatures at Boeing.[18] A 2319 weld filler wire, 0.063-inch diameter, was used in making the welds. Average results for the as-welded specimens are as follows:

Testing Temperature, F	Yield Strength, ksi	Tensile Strength, ksi	K_{Ic}, ksi $\sqrt{in.}$
140	28.0	41.9	28
75	27.0	41.9	29
-320	32.6	58.0	33

The fracture toughness in the as-welded condition is comparable to that obtained from other types of specimens of 2219-T851 parent metal.

Average K_{Ic} values obtained at Boeing for part-through-crack specimens of 2021-T81 plate and welds are 32.5 ksi $\sqrt{in.}$ for parent metal and about 19 ksi $\sqrt{in.}$ in heat-treated weld metal.[18] Yield strength of the parent metal was 65,000 psi, and the yield strength of heat-treated specimens with welds was 40,300 psi.

High-Strength Alloy Steels

Fracture-toughness data for maraging steels and low-alloy steels evaluated as precracked bend-test specimens are given in Table 6. The data indicate that

(1) The fracture toughness of the maraging steels is higher than that of the low-alloy steels at the same strength level.

(2) Vacuum melting contributes to improved fracture toughness of maraging steels over similar material air melted.[19]

(3) K_{Ic} values for AISI 4340 steel, tempered at 500 to 600 F to obtain yield strengths of 216 to 230 ksi, vary from 50 to 56 ksi $\sqrt{in.}$ When tempered at 750 F, the average K_{Ic} value was 70 ksi $\sqrt{in.}$ and the yield strength was 213 ksi.[20,21]

(4) Available data for D6ac steel and 300M steel indicate that these steels have higher fracture toughness than AISI 4340 at comparable strength levels. However, because of the limited data and the tendency for getting considerable scatter in results of K_{Ic} tests, further study appears necessary before making final decisions regarding alloys for new critical applications.

(5) H-11 steel has lower fracture toughness than AISI 4340 steel at comparable yield-strength levels. For this reason, H-11 steel has not been recommended for new structural applications requiring high-strength components.

TABLE 6. AVERAGE PLANE-STRAIN FRACTURE-TOUGHNESS DATA FOR ALLOY STEELS TESTED AS PRECRACKED BEND SPECIMENS AT ROOM TEMPERATURE

Note: Where there are blank spaces in this table, appropriate data for these spaces were not available in the References.

Alloy[a]	Plate Thickness, in.	Heat Treatment	Yield Strength, ksi	Tensile Strength, ksi	Test Specimen Orientation	Average K_{Ic}, ksi $\sqrt{in.}$	$\left(\frac{K_{Ic}}{Y.S.}\right)^2$	Specimen Dimensions, in. Thickness	Width	Crack Length	No. of Tests	Remarks	Reference
18Ni Maraging (AM)			190			112	0.35					Three-point loading	(19)
18Ni Maraging (VIM)			187			160	0.73					Three-point loading	(19)
18Ni Maraging (VAR)	0.5	850 F age, 3 hr	242		T(WR)	84.5	0.12	0.35, 0.45	1,2	0.32-1.8	44	Four-point loading	(20)
18Ni Maraging (VIM)			246			87	0.13					Three-point loading	(19)
18Ni Maraging (VAR)	1.0	900 F age, 3 hr	259		L(RW, RT)	68.4	0.072	0.25-0.8	1,2	0.2-0.8	23	Four-point loading	(20)
18Ni Maraging (300) (VAR)	1.0	900 F age, 3 hr	285		L(RW, RT)	51.8	0.033	0.1- 1.0	1,2	0.1-0.4	38	Four-point loading	(20)
18Ni Maraging (350) (VAR)	4x4 billet	1700 F 1 hr, AC, 1500 F 1 hr, AC, aged 900 F 8 hr	334	342	L(RT)	36.1	0.012	0.394	0.394	- -	2	Three-point loading	(22)
			338	347	T(TW)	36.9	0.012	0.394	0.394	- -	2	Three-point loading	
					T(TR)	36.9	0.012	0.394	0.394		2	Three-point loading	
12Ni-5Cr-3Mo (AM)			175			130	0.55					Three-point loading	(19)
12Ni-5Cr-3Mo (VIM)			186			226	1.48					Three-point loading	(19)
AISI 4130 (AM)			158			100	0.40					Three-point loading	(19)
AISI 4340	1.0	OQ, temper 600 F	230			52.5	0.052	0.25, 0.50	1.0	0.33		Four-point loading	(20, 21)
AISI 4340	1.0	OQ, temper 750 F	213		L(RW)	70	0.092	0.25-1.0					(20, 21)
AISI 4340, Ht. A	3/8	OQ, temper 500 F	217	260	L(RW)	52.6	0.059	0.393	0.97	0.34-0.44	3	Three-point loading	(23)
Ht. B	3/8	OQ, temper 500 F	217	264	L(RW)	50.5	0.054	0.376	0.99	0.20-0.36	3		
Ht. B	3/8	OQ, temper 500 F	223	266	T(WR)	52.9	0.056	0.377	0.99	0.21-0.39	3		
Ht. C	3/8	OQ, temper 500 F	226	267	L(RW)	55.9	0.061	0.376	0.99	0.21-0.44	3		
AISI 4340	1.25	1550 F, OQ, temper 500 F 1+1 hr	228	--	RW	50.0	0.048	1.00			2	Three-point loading	(24)
	1.25	1550 F, OQ, temper 600 F 1+1 hr	216	---	RW	52.4	0.059	1.00			2	Three-point loading	
D6ac		1550 F, OQ, temper 500 F 1+1 hr	231	275		61.4	0.071	0.264	0.707	0.09-0.12	3		(9)
		1550 F, OQ temper 1050 F 1+1 hr	203	218		112	0.30	0.75	1.4	0.27-0.32	2		
300M Forging	4.5x4.5 billet	1600 F, salt quench 1000 F, OQ 110 F, 575 F 2+2 hr	243	296	RW	60.3	0.062	0.5	1.0			Three-point Loading	(25)
5Cr-Mo-V, Ht. A	1/2	OQ, temper 1080 F	213	260	L	35.6	0.028	0.53	1.00	0.16-0.26	3		(23)
Ht. A	1/2	OQ, temper 1080 F			T	32.7		0.53	1.00	0.11-0.28	3		
Ht. A'	1/2	OQ, temper 1080 F			L	34.4		0.54	1.00	0.21-0.29	3		
Ht. A'	1/2	OQ, temper 1080 F			T	31.5		0.54	1.00	0.22-0.29	3		
H-11	Billet[b]	1850 F, OQ, temper 1050 F 2+2 hr	225		T	35.4	0.025	0.75	0.75		2	Three-point loading	(24)
	Billet[b]	1850 F, OQ, temper 1100 F 2+2 hr	194		T	75.5	0.15	1.0	1.0		3		

(a) VAR = Vacuum-arc remelted; VIM = vacuum-induction melted; AM = air melted.

(b) Specimens from mid-radius in 8-inch billet.

Additional fracture-toughness data for a single heat of 18Ni maraging steel subjected to a variety of aging treatments are presented in Table 7. These data were obtained from precracked three-point bend specimens and precracked, compact K_{Ic} tension specimens. The specimens were aged over a range of temperatures from 725 to 1100 F. Aging for 6 hours at 900 F or 24 hours at 800 F resulted in the highest strength levels for this heat. Under some conditions, the results of tests on the compact tension specimens were a little lower than were results of the bend tests, but, overall, the results show relatively good agreement for the two test-specimen designs. K_{Ic} data in Table 7 are a little higher than comparable data for maraging steels in Table 6.

Results of tests on single-edge-notch tension specimens in Table 8 are lower for the 18Ni maraging steels than would be expected from data on bend and compact tension specimens of the 18Ni type in Tables 6 and 7. Data for tests on single-edge-notch specimens of AISI 4140 and D6ac steels also are included in Table 8.

Additional data for D6ac steel are plotted in Figure 5. These data, obtained from several different types of specimens, indicate that a rather marked decrease in toughness occurs for a rather small gain in strength. The double-cantilever-beam specimens referred to in Figure 5 are a modification of the compact K_{Ic} tension specimen, Figure 2 (b), in which the W dimension is much greater. Side notches are required to locate the direction of crack propagation.

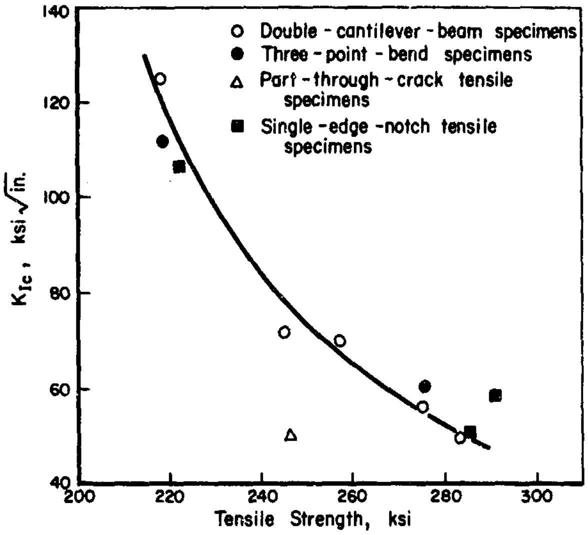


FIGURE 5. VARIATION OF K_{Ic} WITH TENSILE STRENGTH FOR DOUBLE-CANTILEVER, THREE-POINT-BEND, SINGLE-EDGE-NOTCH, AND PART-THROUGH-CRACK TENSILE SPECIMENS OF D6ac STEEL(9,28,29)

TABLE 7. AVERAGE PLANE-STRAIN FRACTURE-TOUGHNESS DATA OBTAINED FROM 1.8-INCH-THICK BEND AND COMPACT-K_{Ic}-TENSION SPECIMENS OF 18NI 250-GRADE MARAGING STEEL(a)(26)

Maraging Treatment(b) Temperature, F	Time, hours	Yield Strength, ksi	Tensile Strength, ksi	K_{Ic} Values from Individual Bend Specimens,(c) ksi $\sqrt{in.}$			K_{Ic} Values from Individual Compact Tension Specimens,(c) ksi $\sqrt{in.}$			Max $\left(\frac{K_{Ic}}{Y.S.}\right)^2$
725	6	190	206	158	158	147	147	138	136	0.69
750	6	203	218	143	136	134	133	127	126	0.50
775	6	213	227	124	116	111	121	112	110	0.37
800	6	227	238	102	96	93	97	93	90	0.20
850	6	253	263	76	73	- -	78	77	76	0.095
900	6	259	266	88	84	81	81	81	79	0.115
950	6	252	261	89	84	82	84	83	82	0.125
1000	6	232	242	88	87	83	88	88	87	0.14
1050	6	204	218	108	105	103	107	106	105	0.34
1100	6	180	198	148	145	- -	- -	- -	- -	0.67
800	24	260	271	71	66	64	70	69	59	0.075
900	24	259	268	82	80	79	82	81	80	0.10
1000	24	209	225	99	95	94	98	95	95	0.22

(a) Composition (weight percent): 18.5 Ni, 7.4 Co, 4.8 Mo, 0.40 Ti, 0.11 Al, 0.006 C, 0.01 Si, 0.06 Mn, 0.007 S, 0.006 P, 0.05 Ca, 0.010 Zr, and 0.002 B (consumable-electrode vacuum melted).

(b) Plate solution annealed at 1500 F and cooled in air.

(c) These specimens were obtained from the longitudinal direction (RW).

TABLE 8. AVERAGE PLANE-STRAIN FRACTURE-TOUGHNESS DATA FOR ALLOY STEELS TESTED AS 1-INCH-THICK SINGLE-EDGE-NOTCH SPECIMENS AT ROOM TEMPERATURE(27)

Alloy	Yield Strength, ksi	Tensile Strength, ksi	Test Specimen Orientation	Average K_{Ic}[(a)] ksi $\sqrt{in.}$	$\left(\frac{K_{Ic}}{Y.S.}\right)^2$	No. of Tests
AISI 4140	177	195	WR	88	0.25	3
D6ac	212	229	WR	96	0.21	1
18Ni[(b)] Marage	230	240	RW	70	0.092	1
18Ni[(b)] Marage	234	246	RW	77	0.11	2

(a) Data obtained from single-edge-notch specimens 1 x 5 x 13 inches with 1.6-inch notch depth.

(b) Mill heat treated.

Effects of variations in testing temperature on strength and fracture toughness of AISI 4340 and H-11 steels are shown in Table 9. As the testing temperature is decreased, the strength increases and the toughness decreases. The toughness decreases continuously over the range of testing temperatures from +200 to -100 F and is not representative of a ductile-brittle transition over a narrow temperature range. Because of this trend, however, fracture-toughness tests on specimens representing critical components should be made at the lowest service temperature for the components.

Fracture-toughness data from compact K_{Ic} specimens and notched-bend specimens for HP9Ni-4Co steels are presented in Table 10. For the lower carbon alloy, there is no apparent effect of temperature on the fracture toughness in the range

TABLE 9. AVERAGE PLANE-STRAIN FRACTURE-TOUGHNESS DATA FOR ALLOY STEELS TESTED AS PRECRACKED BEND SPECIMENS OVER THE TEMPERATURE RANGE -100 F TO 200 F(23)

Alloy	Heat No.	Form	Heat Treatment	Testing Temp., F	Yield Strength, ksi	Tensile Strength, ksi	Test Specimen Orientation	Average K_{Ic}, ksi $\sqrt{in.}$	$\left(\frac{K_{Ic}}{Y.S.}\right)^2$	Specimen Dimensions, in. Thickness	Width	Crack Length	No. of Tests
AISI 4340(1A)	3920569	3/8-In. plate	1500 F, OQ, 500 F 2+2 hr	200	208	259	RW	59.9	0.083	0.39	0.98	0.4	3
				75	217	260	RW	52.6	0.059	0.39	0.97	0.4	3
				-50	231	270	RW	42.1	0.033	0.39	0.99	0.35	1
				-100	235	276	RW	36.9	0.025	0.39	0.99	0.33-0.44	3
AISI 4340(1B)	54927	3/8-In. plate	1500 F, OQ, 500 F 2+2 hr	200	205	260	RW	57.3	0.078	0.38	0.99	0.20-0.34	3
				75	217	264	RW	50.5	0.054	0.38	0.99	0.20-0.36	3
				75	223	266	WR	52.9	0.056	0.38	0.99	0.21-0.39	3
				-50	233	273	RW	42.1	0.033	0.39	0.99	0.36	3
				-100	235	280	RW	31.4	0.018	0.38	0.99	0.20-0.31	3
AISI 4340(1C)	335285	3/8-In. plate	1500 F, OQ, 500 F 2+2 hr	200	209	264	RW	65.6	0.099	0.37	1.00	0.21-0.40	3
				75	226	267	RW	55.9	0.061	0.38	1.00	0.21-0.43	3
				-50	235	274	RW	39.8	0.029	0.38	1.00	0.20-0.35	3
				-100	240	280	RW	33.1	0.019	0.37	1.00	0.20-0.34	3
H-11 (5B)		1-In. Bar	1850 F, OQ, 1030 F 1+1 hr	200	- -	- -	RW	26.1	0.014	1.00	1.00	0.26	1
				75	- -	275	RW	23.3	0.014	1.00	1.00	0.22	1
				-50	- -	- -	RW	17.8	0.005	1.00	1.00	0.21-0.29	3
				-100	- -	- -	RW	16.6	0.004	1.00	1.00	0.21-0.33	3
H-11 (4A)	31207	1/2-In. plate	1850 F, OQ, 1080 F 1+1 hr	200	202	248	RW	50.0	0.061	0.53	1.00	0.22	2
				75	213	260	RW	35.4	0.028	0.53	1.00	0.26	2
				75	204	252	WR	31.5	0.024	0.51	1.00	0.26	2
				-50	219	264	RW	20.8	0.009	0.53	1.00	0.24	2
				-100	231	278	RW	19.7	0.007	0.53	1.00	0.23	1
H-11 (6A)	33015	1-In. bar	1850 F, OQ, 1100 F 1+1 hr	200	198	236	RW	80.6	0.17	1.03	1.00	0.24	1
				-50	210	260	RW	28.1	0.018	1.03	1.00	0.33	1
				-100	220	268	RW	23.2	0.011	1.03	1.00	0.28	1

TABLE 10. AVERAGE PLANE-STRAIN FRACTURE-TOUGHNESS DATA FOR HP 9Ni-4Co ALLOY STEELS OVER THE TEMPERATURE RANGE -110 TO 300 F

Alloy	Form	Heat Treatment	Testing Temp., F	Yield Strength, ksi	Tensile Strength, ksi	Specimen Type[(b)]	Test Specimen Orientation	Average K_{Ic}, ksi $\sqrt{in.}$	$\left(\frac{K_{Ic}}{Y.S.}\right)^2$	Specimen Thickness, in.	Specimen Width, in.	No. of Tests	Reference
HP 9Ni-4Co-0.26C[(a)]	3-In. forged plate	1550 F, OQ, 1000 F, 2+2 hr	75	176	- -	Comp	RW	112	0.41	2.00	4.0	1	(16)
			75	177	184	Comp	WR	99	0.31	2.00	4.0	2	
			100	180	193	Comp	WR	102	0.32	2.00	4.0	2	
			150	175	189	Comp	WR	108	0.38	2.00	4.0	2	
			32	187	197	Comp	WR	102	0.30	2.00	4.0	2	
			0	187	196	Comp	WR	106	0.32	2.00	4.0	2	
			-40	188	197	Comp	WR	111	0.35	2.00	4.0	2	
			-75	187	196	Comp	WR	115	0.38	2.00	4.0	2	
HP 9Ni-4Co-0.45C	3x9x24-In. Billet	1550 F, salt Q 465 F, 6 hr	75	225	273	NB-4	WR	89	0.16	0.480	1.50	6	(30)
			300	192	279	NB-4	WR	83	0.19	0.480	1.50	2	
			-65	- -	- -	NB-4	RW	84	- -	0.480	1.50	6	
			-65	- -	- -	NB-4	WR	78	- -	0.480	1.50	6	
			-65	- -	- -	NB-4	TW	71	- -	0.480	1.50	6	
			-110	242	287	NB-4	WR	62	0.065	0.480	1.50	2	
HP 9Ni-4Co-0.45C	Forging	1500 F, salt Q 475 F, 6 hr	75	225	273	NB-4	RW	101	0.20	0.480	1.50	3	(30)
			-65	- -	- -	- -	TW	80	- -	0.480	1.50	3	

(a) Composition: 0.26C, 0.33Mn, 0.008P, 0.008S, 0.01Si, 8.41Ni, 0.40Cr, 0.48Mo, 0.07V, 3.9Co

(b) Comp = compact K_{Ic} tension specimen; NB-4 = notch bend specimen, 4-point loading

from -75 to 150 F, although there is a slight decrease in yield strength with increasing temperature. For the 0.45 percent carbon alloy, there is a reduction in fracture toughness with a reduction in testing temperature from 75 to -110 F or from 75 to -65 F, as shown in Table 10. This temperature effect is much less pronounced than for AISI 4340 or H-11 steel.

Results of tests on single-edge-notch tensile specimens of 18Ni maraging steel (250 grade) at -110 F are shown in Table 11. The specimens were obtained from various orientations in forgings and plate of air-melted, vacuum-arc-remelted, and double-vacuum-melted alloy. These data again indicate better fracture toughness for the vacuum-melted alloy than for the air-melted alloy. Furthermore, there is only a limited variation in strength and toughness in specimens obtained from various orientations in these large forgings of maraging steel. The toughness values at -110 F are only slightly lower than would be expected from tests at room temperature, although valid data were not obtained for the 1/4-inch-thick specimens at room temperature.

Data in Table 12 were obtained on part-through-crack tension specimens of several high-strength-alloy steels. These data indicate that the 9Ni-4Co-0.44C steel is slightly tougher in the bainitic condition than in the martensitic condition. However, the bainitic treatment resulted in slightly lower strength than the martensitic treatment. The effect of carbon content on the toughness of 300M steel also is indicated in Table 12. The lower carbon content resulted in better toughness at the same strength level. Specimens of D6ac steel (0.47 percent carbon) had slightly better toughness than specimens of 300M steel (0.45 percent carbon) in the same strength range. One interesting point in Table 12 is that the specimens representing the higher toughness steels were more consistent in regard to fracture strength. This is shown in the column headed fracture-strength/yield-strength range. The report from which these data were obtained contains much more information on these steels, particularly 300M.

Boeing data for part-through-crack specimens of alloy steels are shown in Figure 6. At the higher strength levels, the maraging steels have better fracture toughness than D6ac steel or comparable 9Ni-4Co steels. Corresponding data for welded specimens with the part-through cracks in the weld metal are shown in Figure 7.

A comparison of the transverse fracture toughness of four gun tubes (175-mm M113) from -80 F to room temperature is shown in Figure 8. These data indicate a toughness-temperature transition range from about -30 to -60 F. The gun tubes from which these specimens were machined had yield strengths from 180,000 to 185,000 psi. The toughness-temperature transition effect shown in Figure 8 has not been observed for other high-strength steels. However, this type of transition effect might be found if the testing temperatures were at 10 or 20 degree increments in the transition range during testing of other high-strength steels.

Intermediate- and Low-Strength Steels

Plane-strain fracture-toughness tests originally were intended for high-strength alloys, including steels with yield strengths over about 180,000 psi. However, tests have been made on intermediate-strength steels and also on relatively low-strength steels in thick sections. Data from four-inch-thick, compact K_{Ic} tension specimens for AISI 1045, 1144, and 4140 steels are shown in Table 13. Valid data could not be obtained for the 4-inch-thick specimens of AISI 1045 steel at room temperature. The metallographic structure of the AISI 1045 steel consisted of pearlite and ferrite, while that of the AISI 1144 and 4140 steels consisted primarily of pearlite.

TABLE 11. AVERAGE PLANE-STRAIN FRACTURE-TOUGHNESS DATA OBTAINED FROM SINGLE-EDGE-NOTCH SPECIMENS OF 18NI 250-GRADE MARAGING STEEL AT -110F[25]

Alloy and Melting Practice	Product Form[a]	Yield Strength, ksi[b]	Tensile Strength, ksi[b]	Test Specimen Orientation	Average K_{Ic},[c] ksi $\sqrt{in.}$	$\left(\frac{K_{Ic}}{Y.S.}\right)^2$	No. of Tests
18Ni(250) Air Melted	Forging, 13 x 13 in.	256	271	RT	68.3	0.071	1
				RW	64.1	0.062	2
		251	263	WR	60.7	0.059	2
				WT	64.4	0.064	2
		255	270	TW4	54.7	0.046	2
				TW	61.9	0.060	2
	Forging 4.5x13 in.	260	271	RT	81.3	0.098	1
				RW	76.1	0.086	2
				WR	66.1	0.066	2
				WT	76.3	0.075	3
		264	276	TW4	69.1	0.070	3
				TW	54.2	0.043	2
	Forging 4.5x4.5 in.	263	275	RT	79.9	0.092	2
				RW	79.1	0.090	2
		268	278	WR	70.9	0.073	3
				WT	75.3	0.079	3
				TW4	73.4	0.078	2
				TW	74.7	0.079	2
	Forging 1-1/2x13in.	268	279	RT	76.3	0.081	2
				RW	72.1	0.073	2
		268	281	WR	69.5	0.067	2
				WT	67.2	0.063	2
				TW	62.9[d]	0.055	2
	Plate 0.5 x 13in.	274	283	RW	73.6	0.073	1
		272	286	WR	72.7	0.071	2
18Ni(250) Vacuum-Arc Remelted	Forging 13 x 13 in.	259	274	RT	81.8	0.099	1
		260	274	WR	79.5	0.093	2
				WT	80.0	0.093	1
		262	274	TW4	71.9	0.076	2
				TW	81.9	0.098	2
	Forging 4.5 x 13in.	265	276	WR	84.0	0.097	1
				TW	73.7	0.076	2
	Forging 4.5 x 4.5in.	273	281	RT	85.8	0.098	1
				RW	82.5	0.092	2
		272	281	WR	79.9	0.086	2
				WT	82.1	0.091	1
	Plate 1.5 x 13in.	262	276	RT	82.2	0.096	1
				RW	77.9	0.089	2
		267	279	WR	73.4	0.076	2
				WT	78.3	0.087	2
				TW	68.8[d]	0.066	2
	0.5in. Plate	264	275	WR	83.6	0.100	1
18Ni(250) Double-Vacuum Melted	Forging 13 x 13in.	266	280	RT	80.1	0.093	2
		265	279	WR	72.9	0.076	2
				WT	78.3	0.089	2
		265	277	TW4	75.0	0.082	2
				TW	76.9	0.086	2
	Forging 4.5 x 4.5in.	273	283	WR	79.1	0.085	2
				WT	80.8	0.089	2
				TW4	82.4	0.092	2
				TW	73.6	0.074	1

(a) Forging or plate annealed at 1500 F for 1 hour and cooled in air; specimens aged at 950 F for 3 hours.
(b) Tensile properties are for longitudinal specimens corresponding to RT and RW orientations, for transverse specimens corresponding to WR and WT orientations and for short transverse specimens corresponding to TW orientation; TW4 specimens were taken at 45° to the surface.
(c) Single-edge-notch specimens were 1/4 inch thick, 1 inch wide, and 4 inches long.
(d) Data obtained from 0.5-inch-thick compact K_{Ic} specimens.

TABLE 12. AVERAGE PLANE-STRAIN FRACTURE-TOUGHNESS DATA FOR ALLOY STEELS TESTED AS PART-THROUGH-CRACK SPECIMENS AT ROOM TEMPERATURE, SELECTED VALUES[31]

Alloy	Heat Treatment	Yield Strength, ksi	Tensile Strength, ksi	Crack-Depth Range (a), in.	a/2c[(a)] Range	Fracture Strength / Yield Strength Range[(b)]	K_{Ic} Range, ksi$\sqrt{in.}$	No. of Tests
9Ni-4Co(0.44C) Martensitic	1450 F, AC, -100 F 2 hr, 475 F 2+2 hr	240	280	0.063-0.095	0.293-0.360	0.52-0.83	61-75	3
9Ni-4Co(0.44C) Bainitic	1450 F, transfer to furnace at 460 F 8hr AC, 425 F, 2+2 hr	235	275	0.067-0.100	0.331-0.399	0.72-0.88	77-85	6
300M(0.45C)	1600 F, OQ, 575 F 2+2 hr	240	291	0.041-0.086	0.297-0.465	0.48-0.82	52-58	5
300M(0.39C)	1600 F, OQ, 575 F 2+2 hr	241	287	0.080-0.090	0.292-0.334	0.69-0.76	76-80	2
D6ac(0.47C)	1550 F, OQ, 600 F 2+2 hr	244	279	0.069-0.100	0.311-0.470	0.48-0.78	57-66	3
AISI 4340 (0.39C)	1550 F, OQ, 450 F 4 hr	227	274	0.100	0.345-0.371	0.75-0.77	81-82	2

(a) a/2c = crack depth/crack length.
(b) Fracture strength based on cross-section area minus crack area, specimens 0.200 inch thick in test section and 1.5 inches wide.

TABLE 13. PLANE-STRAIN FRACTURE-TOUGHNESS DATA[(a)] OBTAINED FROM COMPACT K_{Ic} SPECIMENS OF CARBON AND LOW ALLOY STEELS[14]

AISI Steel Type	Product Form	Heat Treatment	Testing Temp., F	Yield Strength, ksi	Tensile Strength, ksi	Test Specimen Orientation	Average K_{Ic}, ksi$\sqrt{in.}$	$\left(\frac{K_{Ic}}{Y.S.}\right)^2$	No. of Tests
1045	Plate, 4 in. thick	Heated to 1650 F, cooled in air	25	39		RW	46	1.4	1
			0	40		RW	46	1.3	1
1144	Forging, 4 x 10 x 12 in.	1550 F, OQ, tempered 900 F 6 hr	75	78	122	--	62	0.64	2
			0	78			52	0.45	1
4140	Plate, 4 in. thick	1550 F, OQ, tempered 1200 F 6 hr	75	65	100.9	RW	55	0.71	2
			0	82		RW	52	0.40	1

(a) Compact K_{Ic} specimens were 4 inches thick, 12 inches wide, and 9.92 inches in height ("4T" geometry), with fatigue cracks in the notches.

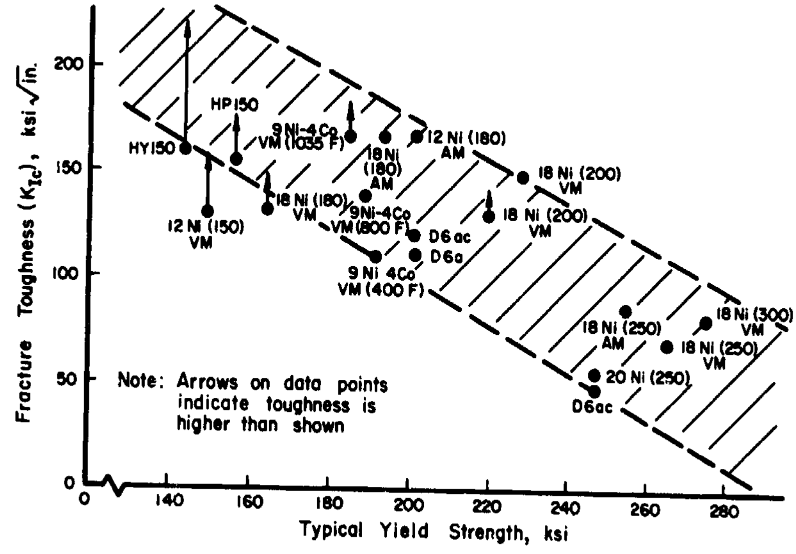


FIGURE 6. PARENT-METAL FRACTURE-TOUGHNESS DATA(32)
AM = air melted; VM - vacuum melted;
GTA - gas-tungsten-arc

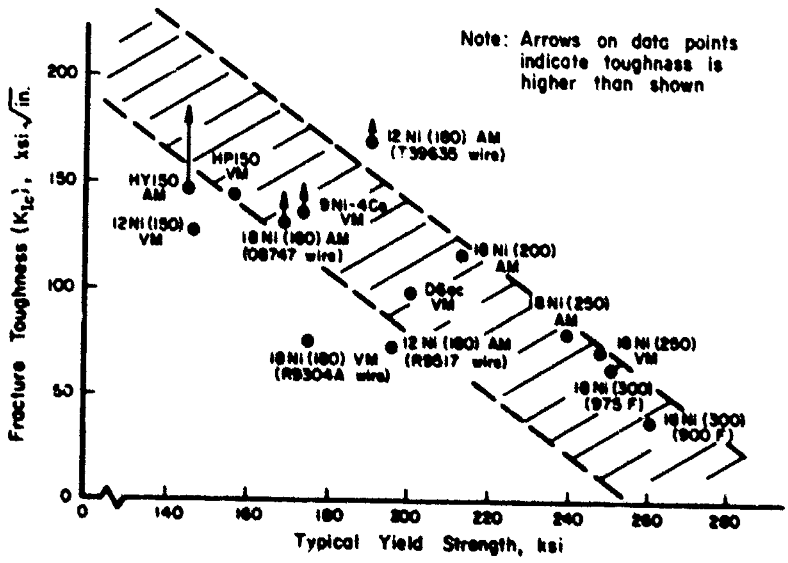


FIGURE 7. GTA (TIG) WELD-TOUGHNESS DATA(32)
AM = air melted; VM = vacuum melted;
GTA = gas-tungsten-arc

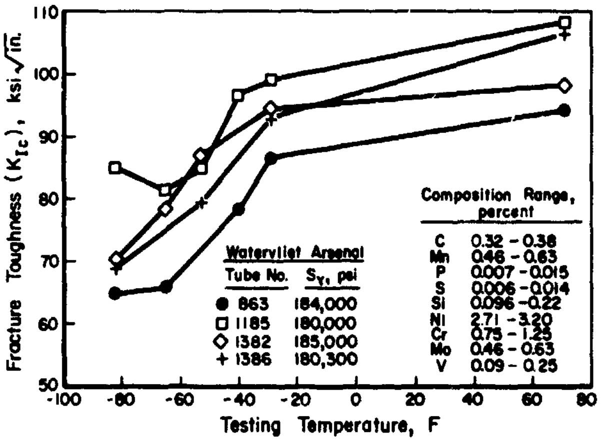


FIGURE 8. TRANSVERSE FRACTURE-TOUGHNESS DATA FROM PRECRACKED BEND SPECIMENS MACHINED FROM 175-MM M113 GUN TUBES[33]

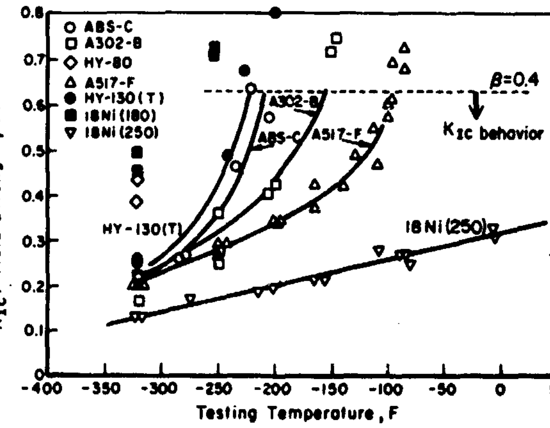


FIGURE 9. EFFECT OF TEMPERATURE ON CRACK-TOUGHNESS PERFORMANCE FOR SEVERAL STEELS TESTED STATICALLY[34]

Results of low-temperature fracture-toughness tests on intermediate-strength and low-strength steels are shown in Figure 9. Valid data are below the dashed line, representing β = 0.4, where $\beta = (1/B)(K_{Ic}/Y.S.)^2$ and B = thickness in inches. Obviously, the intermediate- and low-strength steels have a high degree of temperature sensitivity in regard to fracture-toughness measurement. Tensile-property data for the steels in Figure 9 are shown in Table 14. Results of dynamic tests on precracked bend specimens at low temperatures are shown in Figure 10. Dynamic loading tends to shift the curves to the right. For dynamic loading, data for the HY-type steels (tempered martensite) are in one band and data for the ferrite-pearlite steels (ABS-C, A302B, etc.) are in another band.

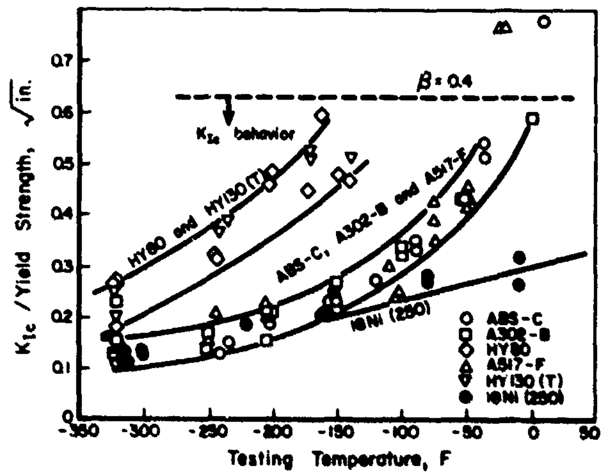


FIGURE 10. EFFECT OF TEMPERATURE ON CRACK-TOUGHNESS PERFORMANCE FOR SEVERAL STEELS TESTED DYNAMICALLY[34]

TABLE 14. STATIC AND DYNAMIC TENSILE PROPERTIES AT ROOM TEMPERATURE OF STEELS FOR LONGITUDINAL SPECIMENS OF 1-INCH PLATE[34]

Steel Type	Yield Strength, 0.2% offset, ksi	Tensile Strength, ksi	Elongation in 1 Inch, percent	Reduction in Area, percent	NDT Temp, F	Dynamic Y.S. at NDT Temp., ksi	Dynamic K_{Ic} Values at NDT Temp., ksi $\sqrt{in.}$
ABS-C	39	63	36.0	66.8	-10	73	50
A302-B	56	88	26.0	67.0	+20	84	55
HY-80	84	99	25.0	74.9	-120	129	80
A517-F	118	129	19.0	65.4	-40	151	92
HY-130(T)	137	143	20.0	70.9	-180	179	88
18Ni(180)	180	189	14.0	66.0	- -	- -	- -
18Ni(250)	246	258	10.5	51.3	- -	- -	- -

Fracture-toughness data obtained on compact K_{Ic} tension specimens from a 12-inch-thick plate of ASTM A533B steel are shown in Figure 11. At -200 F, valid data were obtained on 1-inch-thick specimens, but, at 50 F, a 10-inch-thick specimen was required to obtain valid data. The transition-temperature region for this steel is approximately from 0 to 50 F, based on these fracture-toughness tests.

Fracture-toughness data to -320 F are shown in Figure 12 for several heats each of Ni-Mo-V, Cr-Mo-V, and Ni-Cr-Mo-V low-alloy steel forgings. The data were obtained using compact K_{Ic} specimens. There was more scatter in data for the Ni-Mo-V and Ni-Cr-Mo-V heats than for the Cr-Mo-V heats. Scatter in data appears to be more prevalent in the transition region than in the other parts of the curves. This effect is similar to Charpy V-notch impact data in the transition region of low-strength steels. Because of the variations in fracture-toughness data from heat to heat of the same alloy, tests should be made on a number of heats to obtain a statistical analysis of the fracture toughness of each alloy if the data are to be used in design.

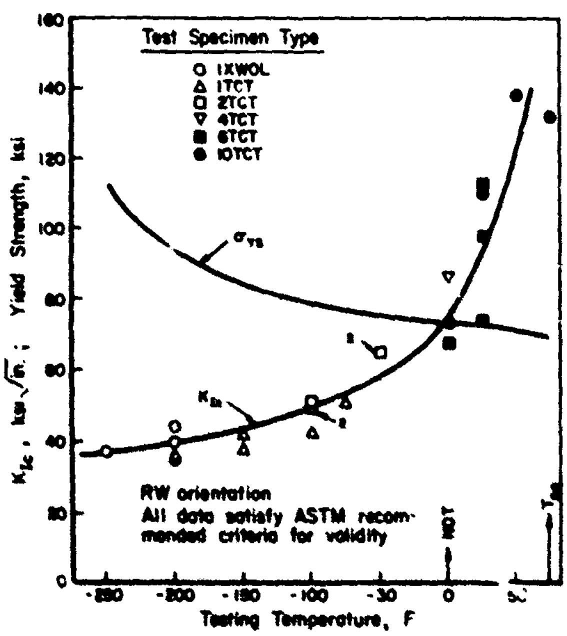


FIGURE 11. FRACTURE TOUGHNESS AT LOW TEMPERATURES FOR A533B STEEL FROM 12-INCH-THICK PLATE(5)

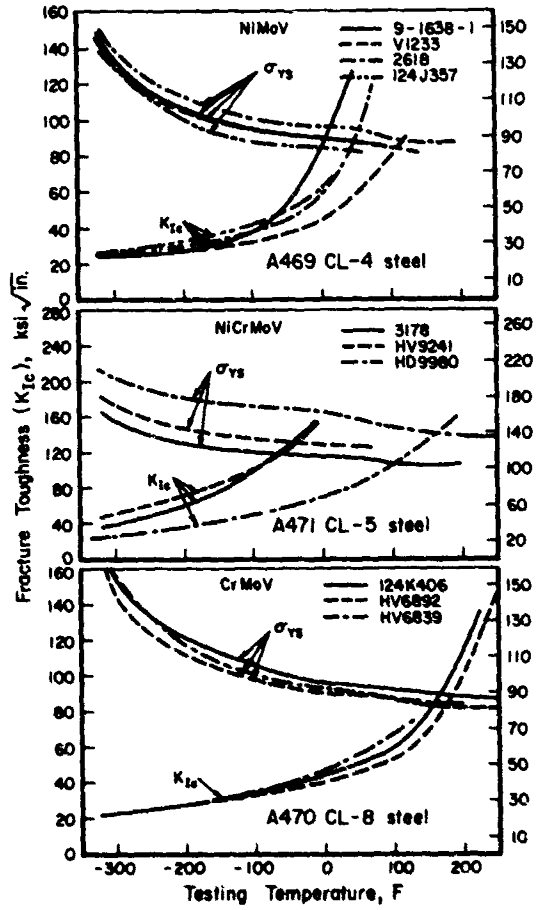


FIGURE 12. EFFECT OF TEMPERATURE ON FRACTURE TOUGHNESS OF THREE TYPES OF ALLOY-STEEL FORGINGS(5)

Precipitation-Hardening Stainless Steels

Precipitation-hardening stainless steels can be heat treated to strength levels at which plane-strain fracture-toughness data can be obtained without having to use extremely large specimens. Data for three-point bend tests on precracked specimens of PH15-7Mo, 17-4PH, AM-355, and A-286 stainless steels are given in Table 15. At a yield strength of 165,000 psi, the cold-worked-and-aged A-286 stainless steel has better fracture toughness than the others in Table 15.

Effects of low and elevated temperatures on the fracture toughness of three types of PH steels are shown in Table 16. Decreasing the testing temperature below room temperature tends to decrease the fracture toughness. Testing specimens of PH15-7Mo stainless steel at 200 F resulted in better fracture toughness than at room temperature.

Fracture-toughness data for PH13-8Mo stainless steel tested as single-edge-notch specimens at -110 F are presented in Table 17. The 0.25-inch-thick specimens were not thick enough for valid data at room temperature. The above data indicate that the fracture toughness of the PH stainless steels is temperature sensitive. Therefore, the fracture-toughness values that should be used in critical-crack size calculations or for comparing alloys should be representative of the lowest service temperature for the component being considered.

TABLE 15. AVERAGE PLANE-STRAIN FRACTURE-TOUGHNESS DATA FOR STAINLESS STEELS TESTED AS PRECRACKED THREE-POINT-BEND SPECIMENS AT ROOM TEMPERATURE

Alloy		Form	Heat Treatment	Yield Strength, ksi	Tensile Strength, ksi	Test Specimen Orientation	Average K_{Ic}, ksi $\sqrt{in.}$	$\left(\frac{K_{Ic}}{Y.S.}\right)^2$	Specimen Dimensions, in. Thickness	Width	Crack Length	No. of Tests	Reference
PH15-7Mo,	Ht.A	Bar	TH1050	- -	- -	L	63.8	- -	0.75	0.75	0.17-0.22	3	(23)
(Code 13)	Ht.B	Bar	TH1050	- -	- -	L	63.0	- -	0.75	0.75	0.18-0.25	3	(23)
PH15-7Mo,	Ht.A	Bar	RH950	173	186	L	57.1	0.095	0.75	0.75	0.15-0.30	3	(23)
(Code 14)	Ht.B	Bar	RH950	178	188	L	50.4	0.080	0.75	0.75	0.17-0.24	3	(23)
17-4PH,	Ht.A	Plate[a]	H900	168	192	L	46.2	0.076	0.51	1.00	0.30-0.44	3	(23)
(Code 15)	Ht.A	Plate[a]	H900			T	36.0	- -	0.51	1.04	0.30-0.33	3	(23)
	Ht.B	Plate[a]	H900	170	197	L	36.8	0.047	0.51	1.00	0.29-0.33	3	(23)
	Ht.B	Plate[a]	H900			T	40.1	- -	0.51	0.995	0.30-0.33	2	(23)
17-4PH, (Code 16)	Ht.B	Bar	H900	209	210	L	51.5	0.061	0.64	0.64	0.22-0.26	2	(23)
AM355,	Ht.A		SCT1000	166	175	L	82.5	0.25	0.77	0.79	0.13-0.22	3	(23)
(Code 17)	Ht.A		SCT1000	163	176	T	85.9	0.28	0.79	0.79	0.25	2	(23)
	Ht.B			167	179	L	80.6	0.24	0.77	0.79	0.18-0.25	3	(23)
AM355,	Ht.A		SCT1000	171	180	L	70.8	0.17	0.66	1.00	0.31-0.33	2	(23)
(Code 18)	Ht.B		SCT1000	160	169	L	80.0	0.25	0.77	0.80	0.20-0.22	2	(23)
A-286			Forging cold worked, aged 1250-1300 F	165	185	--	181	1.2	3.0	3.4	0.65	2	(35)

(a) One-half-inch-thick plate.

TABLE 16. AVERAGE PLANE-STRAIN FRACTURE-TOUGHNESS DATA FOR STAINLESS STEELS TESTED AS PRECRACKED BENT SPECIMENS OVER THE TEMPERATURE RANGE -100 F TO 200 F[23]

Alloy	Heat No.	Form	Heat Treatment	Testing Temp., F	Yield Strength, ksi	Tensile Strength, ksi	Test Specimen Orientation	Average K_{Ic}, ksi $\sqrt{in.}$	$\left(\frac{K_{Ic}}{Y.S.}\right)^2$	Specimen Dimensions, in. Thickness	Width	Crack Length	No. of Tests
17-4PH(15A)	64404	1/2-in. plate	H900	75	168	192	RW	46.2	0.08	0.51	1.00	0.30-0.44	3
				75	- -	- -	WR	36.0	0.04	0.51	1.04	0.30-0.33	3
				-50	183	208	RW	28.9	0.02	0.51	1.05	0.30	3
				-100	190	214	RW	23.4	0.01	0.51	1.06	0.30	3
17-4PH(15B)	64706-1	1/2-in. plate	H900	75	170	197	RW	36.8	0.05	0.51	1.00	0.29-0.33	3
				75	- -	- -	WR	35.5	- -	0.52	[illegible]	0.33	1
				-50	189	217	RW	27.7	0.02	0.51	1.03	0.31-0.38	3
				-100	194	221	RW	27.0	0.02	0.52	[illegible]	[illegible]	2
17-7PH(7A)	36044	1/2-in. plate	TH1050	75	164	183	RW	66.0	0.16	0.52	1.00	0.23-0.34	3
				75	160	183	WR	64.1	0.16	0.51	1.00	0.20	1
				-50	176	200	RW	43.0	0.06	0.53	1.00	0.20-0.26	3
				-100	180	206	RW	43.1	0.06	0.53	1.00	0.20-0.26	3
17-7PH(7B)	890483	1/2-in. plate	TH1050	75	181	198	RW	82.9	0.21	0.50	0.99	0.21	1
				-50	179	201	RW	44.8	0.06	0.50	1.00	0.24	3
				-100	190	213	RW	52.2	0.07	0.50	1.00	0.21	3
17-7PH(7C)	36050-2A	1/2-in. plate	TH1050	75	156	187	RW	64.0	0.17	0.51	1.00	0.21	1
				-50	155	190	RW	51.2	0.11	0.51	1.00	0.22-0.31	3
				-100	180	207	RW	45.0	0.06	0.51	1.01	0.21	2
PH15-7Mo (11A)	61631	1/2-in. plate	TH1050	75	195	205	RW	69.5	0.13	0.51	1.00	0.24	1
				75	183	190	WR	69.1	0.14	0.51	1.00	0.21	1
				-50	203	211	RW	52.7	0.07	0.52	1.00	0.19-0.38	3
				-100	200	207	RW	47.1	0.06	0.51	1.00	0.24-0.28	3
PH15-7Mo (11B)	810047	1/2-in. plate	TH1050	75	- -	194	RW	69.2	- -	0.52	1.00	0.25	1
				-50	184	193	RW	45.6	0.06	0.52	1.00	0.23-0.27	2
				-100	203	213	RW	46.2	0.05	0.52	1.00	0.21-0.28	3
PH15-7Mo (12A)	61631	1/2-in. plate	RH950	200	196	224	RW	87.8	0.20	0.52	1.00	0.26-0.31	3
				75	207	235	RW	42.4	0.04	0.52	1.00	0.20-0.25	3
				-50	218	246	RW	28.1	0.02	0.52	1.00	0.16-0.26	3
				-100	- -	- -	RW	31.9	0.02	0.52	1.00	0.31-0.39	3
PH15-7Mo (12B)	810047	1/2-in. plate	RH950	200	192	218	RW	65.0	0.11	0.52	1.00	0.21-0.35	3
				75	203	230	RW	45.8	0.05	0.51	1.00	0.24-0.30	3
				-50	222	244	RW	30.9	0.02	0.52	1.00	0.20-0.32	3
				-100	232	250	RW	29.3	0.02	0.52	1.00	0.21-0.30	3

TABLE 17. AVERAGE PLANE-STRAIN FRACTURE-TOUGHNESS DATA FOR PH 13-8Mo STAINLESS STEEL FORGINGS TESTED AS SINGLE-EDGE-NOTCH TENSION SPECIMENS AT -110 F[a] [25]

Alloy and Melting Practice	Product Form	Heat Treatment	Testing Temp., F	Yield Strength, ksi	Tensile Strength, ksi	Specimen Orientation	Average K_{Ic}, ksi $\sqrt{in.}$	$\left(\frac{K_{Ic}}{Y.S.}\right)^2$
PH13-8Mo Double-Vacuum Melted	Forging, 13 x 13 in.	Aged 1000 F 4 hr, air cooled	-110	224	234	RW	53.2	0.057
			-110	218	230	WR	57.2	0.065
	Forging, 4.5 x 4.5 in.	Aged 1000 F 4 hr, air cooled	-110	229	235	RW	42.9	0.035
			-110	227	234	WR	41.2	0.033
	Plate, 1.5 x 13 in.	Aged 1000 F 4 hr, air cooled	-110	219	227	RW	47.4	0.046
			-110	226	234	WR	46.8	0.043

(a) Specimens were 0.25inch thick, 1 inch wide, and 4 inches long.

Titanium Alloys

Because of the strength/density advantage of titanium alloys over other alloys for aerospace pressure vessels and for supersoni aircraft, the fracture toughness of titanium alloys has been studied in many laboratories. However, most of these studies have been concerned with plane-stress fracturing of precracked sheet specimens or with exposure of the precracked specimens to various environments such as seawater or liquid propellants to determine stress-corrosion effects. Consequently, only a limited amount of valid plane-strain data have been reported for titanium alloys.

Available room-temperature and low- and elevated-temperature data for solution-treated-and-aged Ti-6Al-4V alloy are presented in Table 18. The yield- and tensile-strength data for the various heats of Ti-6Al-4V alloy indicate that the response to the solution treating and aging is not consistent. Furthermore, the average K_{Ic} values for longitudinal specimens at room temperature vary from 46 to 81 ksi $\sqrt{in.}$ in Table 18.

Available fracture-toughness data on Ti-6Al-4V-2Sn and Ti-6Al-6V-2Sn alloys are presented in Tables 19 and 20. The various solution-treating and aging treatments used for specimens in Table 19 resulted in a wide range of yield strengths and a wide range of average K_{Ic} values. Furthermore, it appears that there is considerable difference in the toughness characteristics of the heat of Ti-6Al-6V-2.5Sn that was subjected to the single-edge-notch tests and the heat that was subjected to the notched-bend tests.

Data in Table 20 are for Ti 6Al-6V-2Sn alloy at -110 F. Those data were obtained using single-edge-notch tension specimens from various orientations in a forging and from plates of 1.5- and 0.5-inch thickness. Specimens from the forging had lower yield strengths and higher fracture toughness than corresponding specimens from the plates. This may have been caused by the higher solution temperature used for the forging. However, because of the high strength levels that can be obtained with the Ti-6Al-6V-2Sn alloy, it is being considered for certain airframe applications. For these applications, it will be desirable to control the heat treatment to obtain a suitable balance between high strength and required fracture toughness for each specific application.

Part-through-crack specimens have been used to obtain fracture-toughness data for Ti-5Al-2.5Sn (ELI) alloy at -320 F.[38] Magnification factors were applied by Kobayashi and Moss to obtain the corrected data shown in Figure 13. From these data, the fracture toughness of the Ti-5Al-2.5Sn (ELI) specimens at -320 F was from 57 to 65 ksi $\sqrt{in.}$ Tests also have been made on specimens of annealed Ti-5Al-2.5Sn (ELI) at -423 F. Results of tests on part-through-crack specimens[38] and precracked bend specimens[39], both representing the RT orientation, indicated average K_{Ic} values of 52 ksi $\sqrt{in.}$[37]

Part-through-crack specimens have been used at Boeing to determine the fracture toughness of as-welded specimens of Ti-6Al-4V (ELI) alloy at room and cryogenic temperatures.[18] The data are plotted in Figure 14. The average tensile properties are as follows for as-welded specimens 0.320 inch thick:

Testing Temperature, F	Yield Strength, ksi	Tensile Strength, ksi	Elongation, percent
75	133	144	7
-320	214	221	4
-423	--	243	--

Average fracture toughness for the as-welded weldment at room temperature was 62.5 ksi $\sqrt{in.}$

Effects of solution temperature on the properties, including fracture toughness, for solution-treated-and-aged Ti-6Al-4V and Ti-4Al-3Mo-1V alloys, are shown in Figures 15 and 16. These alloys were procured as 1/2-inch plate. The fracture-toughness specimens were 1/2 inch thick and 1-1/2 inch wide for four-point loading in bending.

TABLE 18. AVERAGE PLANE-STRAIN FRACTURE-TOUGHNESS DATA FOR Ti-6Al-4V ALLOY IN THE TEMPERATURE RANGE -100F TO 150 F[(a)]

Alloy	Heat No.	Form	Heat Treatment	Testing Temp., F	Yield Strength, ksi	Tensile Strength, ksi	Test Specimen Orientation	Average K_{Ic}, ksi $\sqrt{in.}$	$\left(\frac{K_{Ic}}{Y.S.}\right)^2$	Specimen Dimensions, in. Thickness	Width	Crack Length	No. of Tests	Reference
Ti-6Al-4V	- -	Plate	1750 F, WQ, 1000 F for 4 hr	75	133	143	RW	(75.8)	0.32	0.78	1.5	0.3	[illegible]	(9)
Ti-6Al-4V (20 A)	292457	1-in. plate	1700 F, AC, 1000 F for 4 hr	75	148	157	RW	46.3	0.098	1.00	1.00	0.19-0.30	3	(23)
				75	- -	- -	WR	42.2	0.081	1.00	1.00	0.19-0.30	3	
				-50	- -	144	RW	45.6	0.061	1.00	1.00	0.27-0.35	2	
				-100	155	190	RW	46.2	0.062	1.00	1.00	0.18-0.26	3	
Ti-6Al-4V (20B)	301483	1-in plate	1700 F, AC, 1000 F for 4 hr	75	157	175	RW	47.1	0.094	0.9	1.00	0.20-0.44	3	(23)
				75	- -	- -	WR	37.2	0.056	0.9	1.00	0.20-0.28	3	
				-50	175	176	RW	40.5	0.054	1.00	1.00	0.20-0.38	3	
				-100	- -	180	RW	42.3	0.059	1.00	1.00	0.20-0.30	3	
Ti-6Al-4V (20C)		1-in. plate	1700 F, AC, 1000 F for 4 hr	75	158	167	RW	51.3	0.132	1.00	1.00	0.23-0.39	3	(23)
				-50	177	189	RW	53.0	0.090	1.00	1.00	0.25-0.34	3	
				-100	173	184	RW	53.9	0.095	1.00	1.00	0.20-0.31	3	
Ti-6Al-4V	- -	3-in. forged plate	1750 F, AC, 1000 F for 4 hr	75	144	- -	WR	80.9	0.33	2.00	4.00	2.0	3	(36)
				75	140	148	WR	79.3	0.32	2.00	4.00	2.0	3	
				100	133	141	WR	71.1	0.29	2.00	4.00	2.0	2	
				150	127	136	WR	75.0	0.38	2.00	4.00	2.0	2	
				32	148	155	WR	65.0	0.19	2.00	4.00	2.0	2	
				0	147	155	WR	69.6	0.22	2.00	4.00	2.0	2	
				-40	153	160	WR	71.5	0.22	2.00	4.00	2.0	2	
				-75	159	165	WR	68.1	0.19	2.00	4.00	2.0	2	

(a) Compositions of Ti-6Al-4V alloys

From Reference (9): 3.[illegible]8V, 5.83Al, 0.16Fe, 0.022N_2, 0.006H_2.
(20A): 4.2V, 6.2Al, 0.15Fe, 0.020C.
(20B): 4.3V, 6.5Al, 0.15Fe, 0.030C.
(20C): 4.3V, 6.3Al, 0.15Fe, 0.026C.
From Reference (36): 4.10V, 6.3Al, 0.13Fe, 0.004H_2, 0.023C.

TABLE 19. AVERAGE PLANE-STRAIN FRACTURE-TOUGHNESS DATA FOR TITANIUM ALLOYS AT ROOM TEMPERATURE

Alloy	Heat Treatment	Yield Strength, ksi	Tensile Strength, ksi	Test Specimen Orientation	Specimen Type[(a)]	Average K_{Ic}, ksi $\sqrt{in.}$	$\left(\frac{K_{Ic}}{Y.S.}\right)^2$	No. of Tests	Reference
Ti-6Al-4V-2Sn	1775 F 1 hr, WQ, 1000 F 2 hr, AC	130	141	RW	SEN	82	0.40	4	(27), (36)
Ti-6Al-6V-2.5Sn	1625 F 1 hr, WQ, 1200 F 2 hr, AC	166	170	RW	SEN	60	0.13	2	(27), (36)
	1550 F 1 hr, AC, 1200 F 2 hr, WQ	130	139	RW	SEN	81	0.39	1	
		136	142	WR	SEN	76	0.31	1	
	1500 F 1 hr, AC, 1100 F 2 hr, WQ	137	143	RW	SEN	80	0.34	1	
		137	142	WR	SEN	74	0.29	2	
	1500 F 1 hr, WQ, 900 F 4 hr, AC	186	202	RW	SEN	34	0.03	2	
Ti-6Al-6V-2.5Sn[(b)] (1-in. plate)	1500 F 0.5 hr, WQ, 900 F 4 hr, AC	187	- -	RW	NB	19	0.010		(37)
	1500 F 0.5 hr, WQ, 1000 F 4 hr, AC	183	- -	RW	NB	25	0.019		(37)
	1500 F 0.5 hr, WQ, 1100 F 4 hr, AC	173	- -	RW	NB	31	0.032		(21), (37)
	1500 F 0.5 hr, WQ, 1300 F 4 hr, AC	145	- -	RW	NB	39	0.072		(37)

(a) SEN = single-edge-notch specimens 1 x 5 x 13 inches with 1.6 inch notch depth.
NB = notched bend specimens 1 inch thick and 2 inches wide for three-point loading.

(b) Composition, percent: 5.4Al, 5.5V, 1.9Sn, 0.66Cu, 0.72Fe, 0.026C, 0.025N, 0.007H, 0.16 O.

TABLE 20. AVERAGE PLANE-STRAIN FRACTURE-TOUGHNESS DATA OBTAINED FROM SINGLE-EDGE-NOTCH SPECIMENS OF Ti-6Al-6V-2Sn ALLOY AT -110F [25]

Product Form(a)	Yield Strength, ksi(b)	Tensile Strength, ksi (b)	Test Specimen Orientation	Average K_{Ic},(c) ksi $\sqrt{in.}$	$\left(\frac{K_{Ic}}{Y.S.}\right)^2$	No. of Tests
Forging, 4.5 x 4.5 in.	181	188	RT	55.9	0.095	2
			RW	50.6	0.079	1
	184	197	WR	49.6	0.072	2
			WT	56.1	0.093	2
			TW4(d)	51.7	0.079	1
			TW	52.9	0.082	1
Plate, 1.5 x 13 in.	195	200	RT	41.0	0.044	2
			RW	32.1	0.027	5
	195	202	WR	32.5	0.028	2
			WT	38.3	0.038	3
			TW	24.8(d)	0.017	2
Plate, 0.5 x 13 in.	210	212	RW	32.6	0.025	2
	208	212	WR	29.9	0.021	2

(a) Products from vacuum-arc remelted alloy. Forging heated to 1650 F for 1 hour and quenched in water; plate heated to 1550 F for 15 minutes and quenched in water; all specimens aged at 1050 F for 4 hours and cooled in air.

(b) Tensile properties are for longitudinal specimens corresponding to RT and RW orientations and for transverse specimens corresponding to WR and WT orientations.

(c) Single-edge-notch specimens were 1/4 inch thick, 1 inch wide, and 4 inches long.

(d) TW4 is short transverse orientation with specimen axis at 45 degrees to surface of forging.

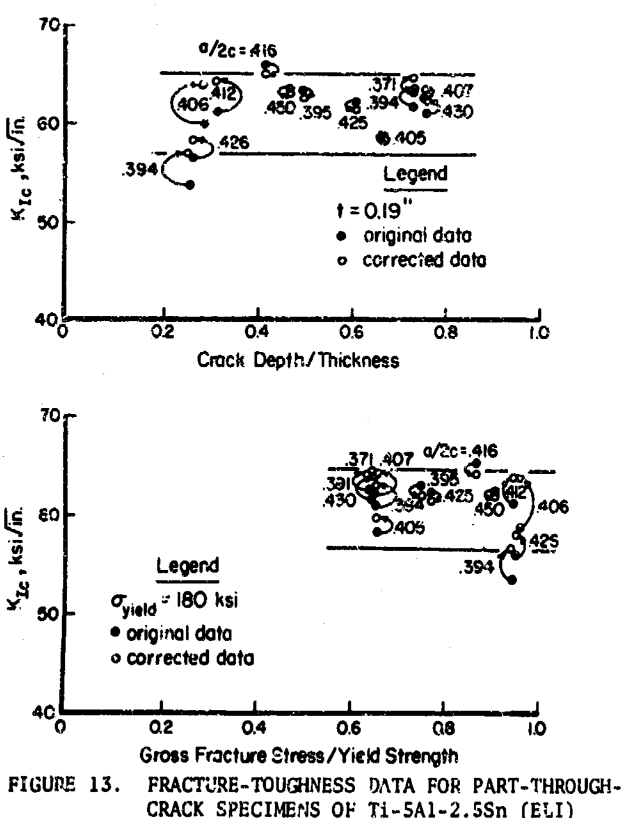


FIGURE 13. FRACTURE-TOUGHNESS DATA FOR PART-THROUGH-CRACK SPECIMENS OF Ti-5Al-2.5Sn (ELI) ALLOY AT -320 F [29,38]

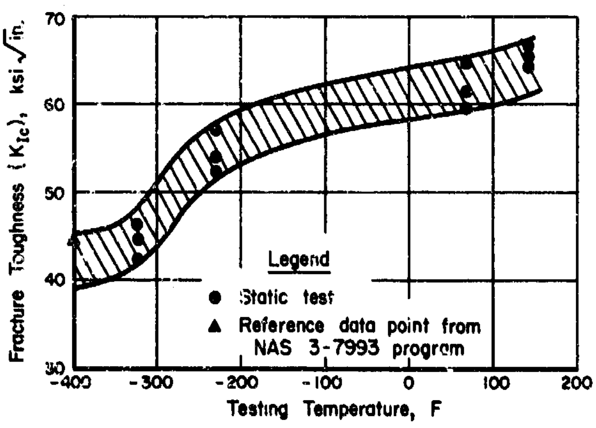


FIGURE 14. FRACTURE TOUGHNESS OF AS-WELDED SPECIMENS OF Ti-6Al-4V (ELI) USING PART-THROUGH-CRACK SPECIMENS[18]

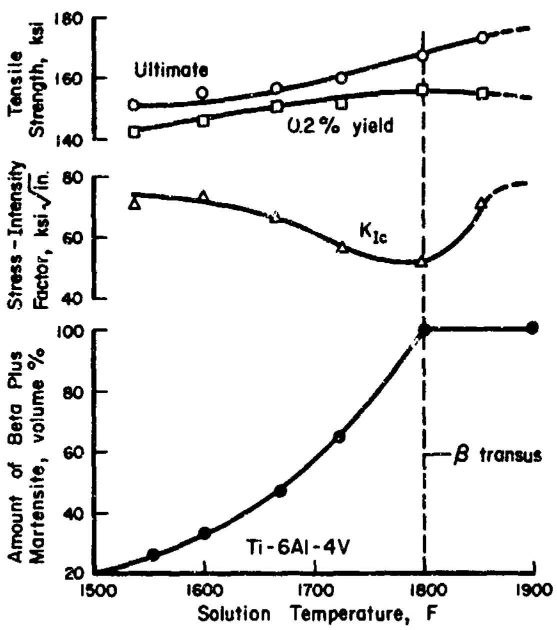


FIGURE 15. EFFECT OF SOLUTION TEMPERATURE ON PROPERTIES OF Ti-6Al-4V WHEN AIR COOLED AFTER SOLUTION TREATMENT AND AGING AT 1250 F FOR 4 HOURS[40]

Composition, percent: 6.4Al, 3.9V, 0.17Fe, 0.03C, 0.003H, 0.15 O, 0.018N.

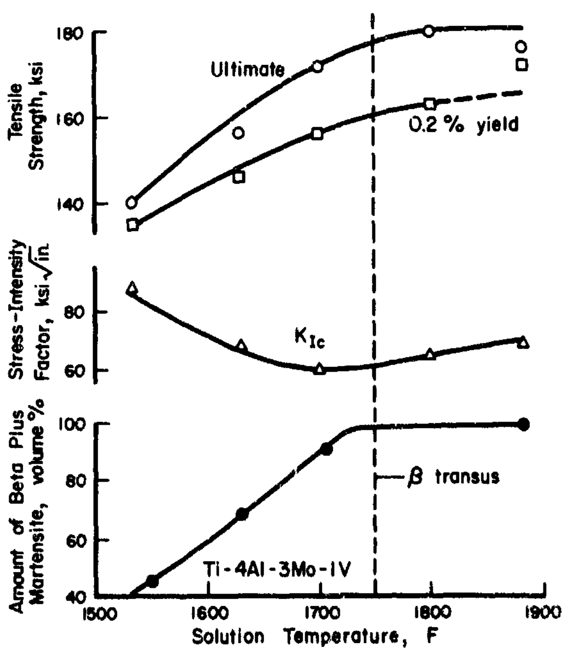


FIGURE 16. EFFECT OF SOLUTION TEMPERATURE ON PROPERTIES OF Ti-4Al-3Mo-1V ALLOY WHEN AIR COOLED AFTER SOLUTION TREATING THEN AGING AT 1100 F FOR 8 HOURS[40]

Composition, percent: 4.5Al, 1.0V, 3.3Mo, 0.10Fe, 0.03C, 0.006H, 0.11 O, 0.009 N.

Nickel-Base Alloy 718

Nickel-base Alloy 718 has been used for certain aerospace applications, such as in pressure vessels for liquid oxygen, because it has good strength and toughness at cryogenic temperatures. Furthermore, it is not subject to ignition in liquid oxygen as are the titanium alloys. Alloy 718 also has been considered for pressure vessels for high-purity hydrogen gas. As part of an evaluation program, part-through-crack fracture-toughness specimens of Alloy 718 were tested to obtain K_{Ic} data for parent metal and welds.[17] Limited data obtained on specimens 0.25 inch thick and 2.5 inches wide indicate that the K_{Ic} values for Alloy 718 were 150 ksi $\sqrt{in.}$ for the parent metal and 95 ksi $\sqrt{in.}$ for the weld metal. Kobayashi's method of analysis was used in calculating these data. Plate-type specimens were machined from 4-1/2-inch-diameter bar stock for these specimens so that the orientation would be equivalent to that of longitudinal specimens from plate. Heat treatment of the alloy consisted of solution annealing at 1750 F for 1 hour, air cooling to room temperature, duplex aging at 1325 F for 8 hours, and furnace cooling to 1150 F and holding at 1150 F for a combined total aging time of 18 hours. Tensile properties of the heat-treated alloy were 174,000 psi yield strength and 195,000 psi tensile strength.

Fracture Toughness of Beryllium

One of the problems in utilizing beryllium for structural applications is its low fracture toughness at room temperature and at low temperatures. A number of attempts have been made to measure K_{Ic} values for beryllium, but special procedures are required. In producing fatigue cracks at notches in the preparation of precracked specimens, the fatigue cracks usually extend completely through the specimen, once a fatigue crack has started, before the fatigue machine can be turned off. If fatigue cracks are produced at elevated temperatures to achieve some degree of control of crack growth, fracture may not occur in the fatigue crack during testing. The probable reason for this is that compressive residual stresses apparently develop at the leading edge of the fatigue crack at the elevated temperatures, reducing the tendency for further crack propagation at this point when loaded at room temperature. Several other methods have been developed for obtaining cracks of controlled lengths in the fracture-toughn[illegible]s.[41,42]

Results of tests on part-through-crack tension specimens of cross-rolled beryllium sheet obtained at Douglas (QMV and PR-20 grade) are shown in Table 21.[41] The calculated K_{Ic} values increased as the flaw-size parameters (a/Q) increased from 0.003 to 0.017. In some instances, the gross fracture stress was equal to or greater than the yield strength. Because of these conditions, not all of the K_{Ic} values represent valid data.

Part-through-crack specimens have been used at Lockheed in determining the fracture toughness of S-200 beryllium sheet.[43] Again, the results were dependent on the flaw size. Results of this study indicate that, for shallow cracks less than 0.010 inch deep, the K_{Ic} value is about 6 ksi $\sqrt{in.}$ for S-200 beryllium sheet.

TABLE 21. FRACTURE TOUGHNESS OF PART-THROUGH-CRACK SPECIMENS OF CROSS-ROLLED BERYLLIUM SHEET AT ROOM TEMPERATURE (41)

Specimen No.	Yield Strength, ksi	Specimen Thickness, in.	Crack Length, in.	Crack Depth, in.	Flaw Size Parameter, a/Q, in.	Gross Fracture Stress, ksi	K_{Ic}, ksi $\sqrt{in.}$
BC4-11	58.0	0.030	0.069	0.013	0.012	59.1	12.7
BC4-1	58.0	0.030	0.047	0.006	0.009	57.5	10.7
BC4-2	58.0	0.030	0.099	0.013	0.014	56.8	12.9
BC4-20	58.0	0.030	0.039	0.009	0.007	57.7	9.7
BC2-3	59.0	0.040	0.058	0.013	0.011	57.6	11.7
BC16-9	62.0	0.040	0.144	0.016	0.017	56.6	14.4
BC16-7	62.0	0.040	0.020	0.004	0.003	52.7	6.0
BC16-20	62.0	0.040	0.044	0.012	0.009	60.7	11.2
BC16-19	62.0	0.040	0.028	0.008	0.006	62.5	9.3
BC16-7	62.0	0.040	0.060	0.012	0.011	61.3	12.4
BC16-14	62.0	0.040	0.074	0.014	0.013	62.2	13.8
BC16-13	62.0	0.040	0.084	0.016	0.015	59.8	14.1
BC16-16	62.0	0.040	0.124	0.016	0.017	59.2	14.9

The influence of loading rate and testing temperature on fracture toughness of hot-rolled AMS7902 beryllium sheet is shown in Figure 17.(44) Center-cracked and part-through-crack specimens were tested at various loading rates and temperatures. The objective was to test fracture-toughness specimens under more rigorous stress-temperature environments than would be expected in service. The resulting minimum K_{Ic} value of approximately 11 ksi $\sqrt{in.}$ should be relatively insensitive to further changes caused by reducing the testing temperature or increasing the loading rate. This value should be suitable for design purposes, because it allows for deviations in service exposures.

Fracture toughness of hot-pressed S-200-grade beryllium has been determined over the temperature range from -320 to 500 F at Westinghouse using WOL-type specimens that are similar to compact K_{Ic} specimens, except for the loading-hole arrangement.(45) The room-temperature value for as-pressed beryllium was 20 ksi $\sqrt{in.}$ Additional data are shown in Figure 18. The beryllium was nearly isotropic in regard to fracture toughness, although it was anisotropic in regard to its tensile properties. On loading the specimens, the crosshead speeds were varied over a range from 0.005 to 2.0 inches per minute. Variations in rate of deformation had no detectable effect on the fracture toughness. Solution treating at 2100 F and aging at 932 or 1385 F caused a marked reduction in fracture toughness, as noted in Figure 18.

In a study at the Lawrence Radiation Laboratory using precracked single-edge-notch specimens, K_{Ic} values of about 13 ksi $\sqrt{in.}$ were obtained for N50A-grade and S-200-grade beryllium sheet.(42) Yield strength was 28,000 psi for the N50A-grade and 40,000 psi for the S-200-grade beryllium.

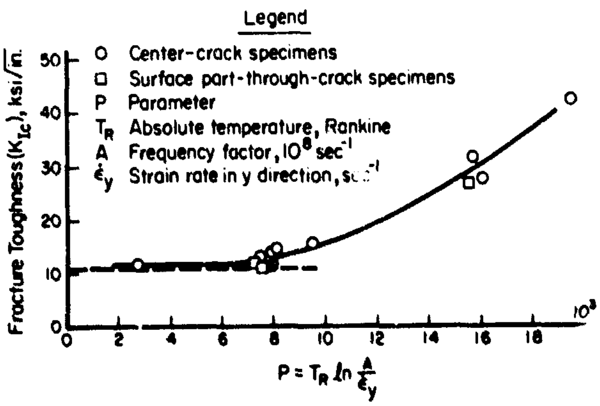


FIGURE 17. FRACTURE TOUGHNESS OF AMS7902 BERYLLIUM AS FUNCTION OF TEMPERATURE AND STRAIN RATE(44)

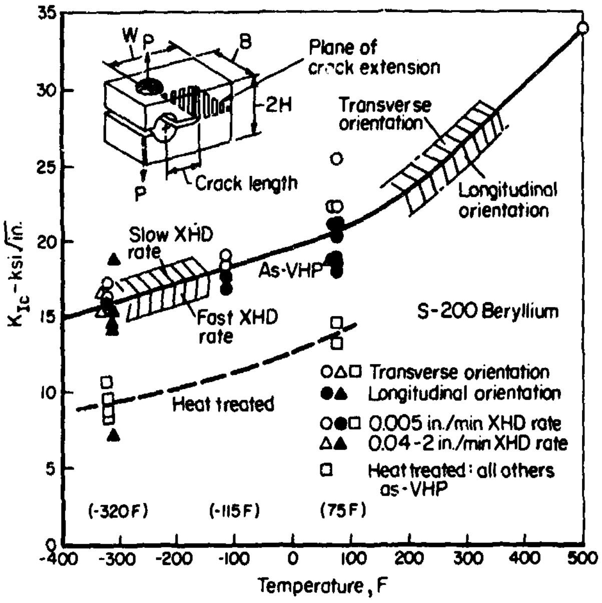


FIGURE 18. FRACTURE TOUGHNESS OF HOT-PRESSED S-200 GRADE BERYLLIUM[45]

APPLICATION OF K_{Ic} DATA

For plane-strain conditions, one is concerned with surface cracks and internal cracks. The techniques for application of plane-strain parameters to structures with surface and internal cracks discussed in this section are according to the work reported by Tiffany and Lorenz[46] and Tiffany and Masters.[4] In the flaw-size parameter, $\left(\frac{a}{Q}\right)$, for surface cracks, a is the crack depth and Q is the flaw-shape parameter from the curves in Figure 19. Equations for the critical flaw-size parameters, $\left(\frac{a}{Q}\right)_{cr}$, for surface cracks and internal cracks are given in Figure 20. Development of these equations is discussed in the references.[4,46,47]

If we consider that a high-strength pressure vessel is subjected to proof test without failure, the largest possible flaws in this vessel will have a flaw-size parameter as indicated by $\left(\frac{a}{Q}\right)_{cr}$ at proof stress in Figure 20. Since the operating stress is lower than the proof stress, any cracks in the vessel would have to grow to the size represented by $\left(\frac{a}{Q}\right)_{cr}$ at operating stress before fracturing would occur at the operating stress level. Thus, the proof stress may be considered as a final nondestructive inspection test, assuming failure does not occur during proof testing. The initial nondestructive-inspection procedures should be of sufficient sensitivity to ensure that no cracks are present approaching the size represented by the critical flaw-size parameter, $\left(\frac{a}{Q}\right)_{cr}$, at the proof stress.

This crack size is directly dependent on the K_{Ic} value and the stress level, as shown in Figure 20.

There are several mechanisms by which crack growth can occur in a structure in service. Among these are fatigue and stress corrosion. Information on the effect of fatigue stressing can be gained by testing a surface-cracked specimen at maximum stresses representing some initial stress intensity, K_{Ii}, less than the critical stress intensity for the initial crack size, $\left(\frac{a}{Q}\right)_i$. The relationship is:

$K_{Ii}=1.95\ \sigma \left(\frac{a}{Q}\right)_i^{1/2}$. On fatigue loading, the crack will grow and the growth rate can be related to the stress intensity level. Furthermore, failure will occur when the crack reaches critical size at maximum stress or:

$$K_{Ic} = 1.95\ \sigma\left(\frac{a}{Q}\right)_{cr}^{1/2}$$

The stress limitations and crack-size limitations for these tests are the same as for determining the K_{Ic} value using precracked specimens. Further discussion of the application of fracture-toughness parameters to fatigue and stress-corrosion problems are beyond the scope of this report.

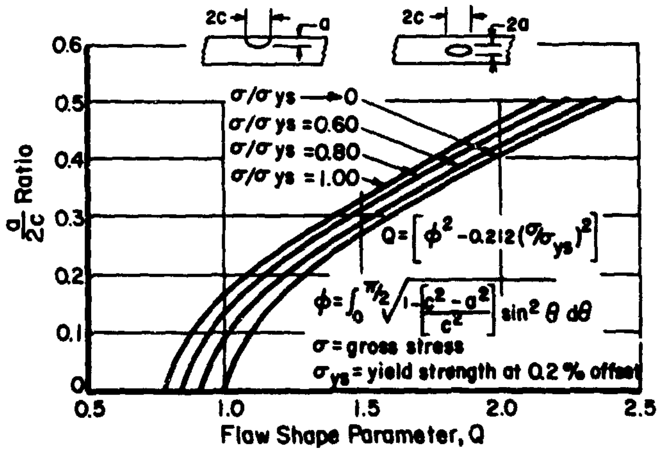


FIGURE 19. FLAW-SHAPE PARAMETER CURVES FOR SURFACE AND INTERNAL CRACKS[4]

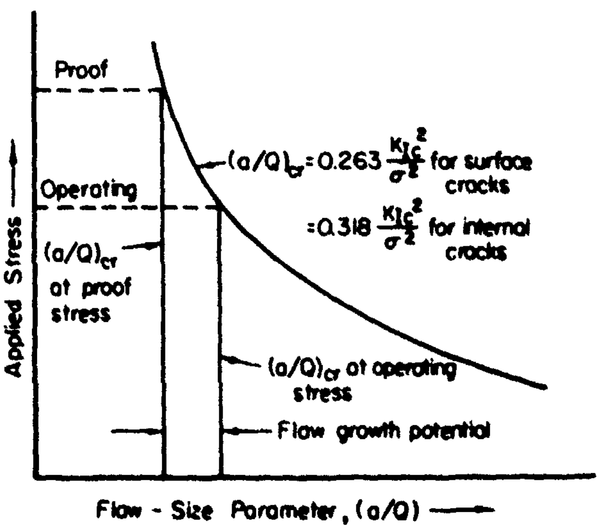


FIGURE 20. DIAGRAM OF MAXIMUM FLAW-SIZE PARAMETER AT PROOF STRESS AND FLAW-GROWTH POTENTIAL BEFORE FAILURE AT OPERATING STRESS ASSUMING PRESENCE OF SURFACE OR INTERNAL FLAWS PERPENDICULAR TO DIRECTION OF APPLIED STRESS

Note: Diagram modified from similar diagram by Tiffany and Lorenz.[46]

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Plane-strain fracture toughn

13. ABSTRACT

Plane-strain fracture-toughness (K_{Ic}) parameters may be used to estimate critical flaw sizes in structural metals subjected to known stresses at specified temperatures. Previous toughness parameters for evaluating high-strength alloys provided only empirical data that could not be used directly in design. This report contains the first compilation of available K_{Ic} data and is the result of considerable interest during the past few years in developing test methods for obtaining these data.

The report is divided into sections on

Aluminum alloys,
High-strength alloy steels
Intermediate- and low-strength steels,
Precipitation-hardening stainless steels
Titanium alloys
Nickel-base Alloy 718
Beryllium.

Data on the aluminum alloys are limited to the 2000- and 7000-series alloys. The high-strength alloy steels include the maraging steels, 9Ni-4Co steels, and lower alloy steels such as AISI 4340, D6ac, 300M, and H-11. The intermediate-strength steels include those that have been considered for submarine hulls, atomic-reactor vessels, and steam-turbine rotors. Data for the stainless steels are limited to the precipitation-hardening grades.

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